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Status, Trends and Implications of Carbon Fiber Material Use

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STATUS, TRENDS AND IMPLICATIONS OF CARBON FIBER MATERIAL USE

by

ECON, Inc.
Princeton, NJ 08540

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Project Officer

Benjamin L. Blaney
Office of Research and Development
Industrial Environmental Research Laboratory
Cincinnati, OH 45268

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OH 46268

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16. ABSTRACT

THIS STUDY ESTIMATES THE FUTURE USAGE OF CARBON FIBER COMPOSITE MATERIALS IN BOTH CONSUMER AND INDUSTRIAL PRODUCTS, AND THE RESULTANT ECONOMIC IMPACT OF THE DISPOSAL OF THESE PRODUCTS AND INDUSTRIAL SCRAP IN BOTH THE MUNICIPAL AND INDUSTRIAL WASTE STREAMS. THE TECHNICAL AND ECONOMIC SUBSTITUTABILITY OF CARBON FIBER COMPOSITE MATERIALS FOR MATERIALS NOW IN USE IS ANALYZED, AND THE MAJOR USES OF THIS MATERIAL FORECASTED. POTENTIAL PROBLEMS RELATING TO THE DISPOSAL OF PRODUCTS CONTAINING CARBON FIBER MATERIALS ARE ANALYZED, AND ESTIMATES MADE OF THE ECONOMIC IMPACTS OF THE DISPOSAL OF THESE PRODUCTS FOR ALTERNATIVE SCENARIOS THAT COVER A WIDE RANGE OF DISPOSAL TECHNOLOGIES. THE ECONOMIC IMPACT OF THE DISPOSAL OF PRODUCTS AND INDUSTRIAL SCRAP CONTAINING CARBON FIBER COMPOSITE MATERIALS IS FOUND TO BE INSIGNIFICANT FOR ALL OF THE SCENARIOS INVESTIGATED.

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FOREWORD

When energy and material resources are extracted, processed, converted and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This study deals with the status and trends of the use of carbon fiber (CF) composite materials in both consumer and industrial products, and the economic impacts of the disposal of consumer and industrial products and industrial wastes containing this advanced structural material. The purpose of this assessment was to provide an economic basis for subsequent policy and decision making with respect to the disposal of products containing CF materials. As such, this report should be particularly useful to policy analysts in the several federal agencies concerned with evaluating the potential impacts of the widespread use of CF materials in consumer and industrial products. For additional information on this subject, the reader may contact the Energy Pollution Control Division, Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio 46268.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

The overall objective of this study was to determine whether or not the future use of carbon fiber or graphite reinforced plastics (GRP) in either consumer goods or the industrial sector will be large enough to cause a disposal problem. In making this determination, it was necessary to analyze the technical and economic substitutability of GRP for materials currently in use. This analysis is sensitive to the projected price of GRP, development of competing technologies and government policies. On the basis of this analysis, the major uses of GRP were forecasted.

The economic and technical incentives for the use of carbon materials are discussed for consumer goods such as sporting equipment and musical instruments and then for applications in the industrial sector, including aerospace, automotive, trucking and other miscellaneous industries. The economic evaluation of carbon fiber substitution for metal in a truck's leaf spring and for fiberglass in both a Boeing 747 and 767 cabin interior is presented as two of the most likely applications of carbon fiber composites. The technical advantages in general are derived from the high strength-to-weight and stiffness-to-weight ratios of graphite reinforced plastics. The economic incentives are varied. In sporting goods, the producers' incentives are incremental profits which can be accrued from the sales of composite items. Incentives for the use of GRP in automobiles are largely a function of the cost of competing materials. In the aerospace and trucking applications, incentives to the manufacturer include the increased design flexibility and reduced production energy requirements, while the incentives to the operators stem from reduced fuel consumption and thus reduced operating expenses or increased revenue.

The magnitude of the disposal problem was then determined. These forecasts and the technical issues involved in the disposal of GRP through both municipal and industrial incineration are discussed. Finally, the economic impact of the disposal of carbon fiber is evaluated, first for the municipal and then the industrial waste stream, under five different scenarios each, in order to test the sensitivity of the results to alternative mixes of disposal techniques that may develop in response to general economic pressures and government policies.

This report is submitted in fulfillment of Contract No. 68-03-2857 by ECON, Inc. under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period September 20, 1979 to September 19, 1981, and the work was completed as of September 19, 1981.

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SECTION 1

INTRODUCTION

GENERAL BACKGROUND

Carbon fibers were first produced for industrial use nearly 100 years ago as part of the search for an incandescent lamp filament. During the 1950s stronger fibers were developed and later embedded in a resin binder to produce what is known as Graphite Reinforced Plastic (GRP) composites.*

GRP offers structural characteristics which portend greatly increased uses of carbon fibers in the future. The use of carbon fiber in composites ranges from products such as golf clubs and tennis racquets to the most advanced aircraft or aerospace applications. The aircraft industry has taken advantage of the light weight and high strength of carbon fiber in the application of GRP to secondary structural items such as flaps, spoilers and movable surfaces. For the newer transport aircraft, the resulting advantages in payload and performance have become important features to the overall design of these airplanes. The most recent designs for military aircraft now moving into production employ GRP as primary structures. The McDonnell-Douglas F-18 "Hornet" built for the Navy has composites as load-carrying wing surfaces as well as secondary structures. In the automobile industry the Ford Motor Company has been actively evaluating GRP for achieving their 1985 fuel consumption requirements. These applications of GRP will in all likelihood utilize the largest quantity of carbon fiber produced during the next few years.

In general these advantages create economic incentives to both the consumer and manufacturer. In the case of automotive uses the incentives to manufacturers are a function of the relative price of competing lightweight materials, whereas the consumer incentive lies in the potential fuel savings. In some applications, such as sporting goods, only the economic incentives to the manufacturer could be quantified, as it was not possible to attach an economic value to the increased utility a consumer could derive (for example) from improved stiffness in golf club performance.

Inadvertent or uncontrolled disposal of GRP could cause damage to electrical equipment and/or health impacts. In 1978 NASA reported that "the only proven hazard of working with graphite fibers lies in their effects on unprotected electrical and electronic equipment." The same NASA report also indicates that although the health implications of carbon fiber release have not been specifically investigated, the diameter and length of typical carbon fibers appear to rule out a significant risk to human health from environmental disposal unless there is degradation or breakdown of the fiber diameter in the disposal process [1].

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*In this study the terms graphite (or GRP) and carbon fiber (or carbon fiber material) are used interchangeably. Use of one rather than the other in a given application generally reflects the customary usage in the literature of that application.

Three options have been identified for the disposal of GRP:

1. Landfill
2. Incineration
3. Reuse.

Current data indicates that both the fibers and resins are stable as a function of time. If subsequent experience and experimentation support this claim, it is likely that landfill will not cause equipment or health problems. On the other hand, in many areas access to landfill facilities is restricted, and landfill is recognized as a solid waste disposal technique that is both economically and esthetically undesirable [2]. Uncontrolled incineration of GRP implies the possibility of damage to electronic and electrical machinery, although it is likely that this possibility could be minimized by the use of pollution control devices at an increased cost. Although it is possible to reuse scrap fiber, at the present time it does not appear to be economically practical to reuse the fiber once it has been embedded in the resin.

OBJECTIVES AND APPROACH

The overall objective of this study is to determine whether or not the future use of carbon fiber or GRP in either consumer goods or the industrial sector will be large enough to cause a disposal problem. In making this determination, it is necessary to analyze the technical and economic substitutability of GRP for materials currently in use. This analysis is reported in Sections 3 and 4 and is sensitive to the projected price of GRP, development of competing technologies and government policies.

On the basis of this analysis, the major uses of GRP must be forecasted, and the magnitude of the disposal problem must then be determined. Section 5 through 7 describe these forecasts and the technical issues involved in the disposal of GRP through incineration. The forecasts of interest are the projected uses of carbon fiber composites both in consumer products and in industrial goods in the year 1990. Since the useful lives of the end uses range from five to ten years for sports equipment to 20 or more years for aerospace items, most of the carbon fiber will not enter the waste stream until the early 2000s. Assuming a steady state situation during those years, the total amount of carbon fiber used by manufacturers in a given year in the 1990s will enter the waste stream in the same, albeit undefined, year. This period is referred to in the report as "post 1990." The economic cost of electrical equipment failures caused by fiber release during GRP disposal is determined in Sections 8 and 9, first for the municipal and then industrial waste streams. Five different scenarios are evaluated for each waste stream in order to test the sensitivity of the results to alternative mixes of disposal techniques that may develop in response to general economic pressures and government policies.

LIMITATIONS

It should be pointed out that this study only addresses the economic impact of electrical failure which may result from the incineration of carbon fiber composite material. The study does not include economic effects from the incineration of raw carbon fiber or prepreg, as their manufacturers were found both to be very much aware of potential hazards and to minimize their scrap. Furthermore, due to insufficient data, the economic impact of potential health effects was not quantified.

Moreover, the study findings and conclusions are based on projections of carbon fiber use as well as estimates of emissions factors for carbon fiber incineration under various particulate control systems. Although considerable effort was made to account for these uncertainties, the projections of future carbon fiber material use are dependent on individual industry decisions and can be significantly impacted by a product decision in a large aerospace firm, for example. The "worst-case" scenarios accounted for some such changes, but it remains possible that even larger increases in carbon fiber use could occur within the next decade, especially if its price is lowered to a level competitive with more conventional materials.

REGULATORY BACKGROUND

Federal actions which tend to influence the use of carbon fiber were subdivided into: 1) energy policies which generally encourage development of lightweight materials and 2) policies and regulations which address potential health, environmental and product reliability issues. A general discussion of the major federal policies is followed by a complete listing of all the recent appropriate laws and regulations.

Energy Policies Which Encourage the Use of High Strength-to-Weight Materials

Perhaps the most influential piece of federal legislation in the area of policy is the Energy Policy and Conservation Act of 1975. This act and subsequent regulations of the National Highway and Safety Administration (NHTSA) call for the production weighted corporate average fuel economy of 27.5 mpg by 1985. The NHTSA regulations additionally spell out a progression of required annual standards as follows:

Model Year	79	80	81	82	83	84	85
Standard, mpg	19	20	22	24	26	27	27.5

The penalty for noncompliance is an assessment of $10 per automobile per mpg in excess of the standard. If for example General Motors had a corporate average fuel economy of only 25 mpg in 1983, then the penalty would be $50 million if the company's production were five million cars.

It is likely that the post-1985 standards will be higher, whether they are set by Congress and NHTSA or dictated by the marketplace. Although the recent change in administration has led to the rejection of the fuel efficiency standard regulations such as proposed in the Jackson-Magnuson bill [3], market share competition both on the national level and internationally will provide a similar incentive for the improvement of fuel efficiency in post-1985 automobiles.

The impact of the legislation on the domestic automobile industry has been dramatic. The manufacturers face an extremely complex planning problem. The problem involves allocating scarce investment capital and existing resources among the most cost-effective and promising fuel saving technologies. The final decisions must result in designs that meet consumer preferences at the same time that they meet the fuel economy standards.

When analyzing the impact of the standards on the demand for lightweight materials, it must be kept in mind that weight reduction is one of many strategies open to manufacturers. In addition to other well known fuel savings technologies such as diesel engines or "lock-up" automatic transmissions, manufacturers can also encourage changes in the composition of the fleet. At the extreme, a company could minimize technological improvements and sell nothing but compacts in order to comply. On the other hand the potential for profit has always been greater on the midsized and full-sized cars and as a result the manufacturers strive to keep these models in the fleet. Studies [4] have shown that standards will require the production weighted average inertia weight to fall from about 4,000 lbs. (1800 kg) in 1978 to 3100 lbs. (1400 kg) by 1985.

In order to reduce vehicle weight and still maintain sales attributes, automotive structures and materials are being closely examined. Greater use is being made of materials such as high strength low alloy (HSLA) steels, aluminum and a variety of plastics materials, including fiberglass reinforced plastics. With extensive use of these materials it may be possible for the manufacturers to produce an automobile that will meet the 1985 regulations and still find market appeal.

In general any policy which encourages an artificial price for transportation fuels has the potential for altering the economic incentives to development of lightweight materials. The effective price of crude oil was regulated during the 1970s and as such the price of gasoline, diesel and aviation fuels were lower than they otherwise would have been. The present decontrol of crude oil along with the automotive fuel economy standards make lightweight materials including carbon fiber more attractive for the 1980s.

Policies Which Address the Impact of Carbon Fiber on Society

Health Issues--

Carbon fiber composites will have a variety of impacts that relate to human health. The beneficial aspects will result from the increasing use of advanced composites in medical instrumentation and devices. As graphite reinforced x ray equipment becomes more common, average exposure of the public to standard diagnostic x rays will decrease. Computed Tomography (CT) is a new technique in general diagnostic x ray with which soft tissues and organs not normally visible can be inspected radiographically. Because of the degree of contrast required and relatively small variations in x ray absorption of body tissues, minimal x ray absorption and a concurrent high degree of rigidity are needed in the patient support structures. These requirements are both met with graphite-epoxy composites to a degree not attainable with other materials. The full benefits to be derived from CT body scanning are not yet known as the method is still experimental; however, it is expected that this method will rapidly become accepted as a specialized diagnostic tool, much in the manner that CT brain scanning has become the diagnostic method of choice for examination of possible brain lesions.

The potential benefits to be gained from implanted advanced composite prostheses are great. Dental surgeons have for decades sought a material for an artificial tooth root implanted through the gingiva into the jaw bone, to provide support for a tooth bridge or complete denture. Total joint replacement such as hip arthoplasty could be another important application. On a prorated population basis, it is estimated that over 100,000 such operations are performed in the United States each year. The less exotic use of advanced composites for external prostheses and medical supports should develop rapidly as the materials become less expensive. This use will result in the qualitative benefits of increased comfort and mobility to the lame and handicapped.

The filamentary structure of high performance fibers presents the most likely potential hazard to human health of advanced composites. Current NIOSH criteria for a recommended standard for occupational exposure to fibrous glass [5] distinguish between fibers that are larger than 3.5μ m in diameter and those that are smaller than 3.5μ m in diameter.

> "The primary health affects associated with the larger diameter fibers involve skin, eye and upper respiratory tract irritation, a relatively low incidence of fibrotic (lung) changes and preliminary indications of a slight excess mortality risk due to nonmalignant respiratory diseases. In this regard, NIOSH considers the potential hazard of fibrous glass to be greater than that of nuisance dust but less than that of coal dust or quartz. With small diameter fibers, much less information on health is available.... On the basis of currently available information, NIOSH does not consider fibrous glass with a diameter of less than 3.5μ m to be a substance that produces cancers as a result of occupational exposure. However, the smaller fibers can penetrate more deeply into the lungs than larger fibers, and until more definitive information is available, the possibility of potential hazardous effects warrant special consideration. The recommended environmental levels are based on evidence in those instances where exposure to asbestos and fibrous glass can be compared, and considering the limitations and deficiencies of such data, fibrous glass seems to be considerably less hazardous than asbestos. In addition,... NIOSH considers that until more information is available, the recommended standard can also be applied to other manmade mineral fibers."

The last sentence is applicable to carbon fibers. Currently all the high performance fibers are manufactured with diameters larger than 8μ m and fall within the large diameter fiber category. As such they should have little health impact other than as an irritant to the skin, eyes and upper respiratory tract. A concern is that fibers smaller than 3.5μ m in diameter may be subsequently formed in the handling or disposal of carbon fiber materials. Filaments could break or splinter while the fibers are handled and processed into composites, and when composite components are machined. Small fibers could potentially also be released by a burning composite structure. Filament diameters may also be made smaller in the future as methods for handling gossamer threads are improved, especially if these filaments were to have improved mechanical properties. For example, the SIC whiskers made by EXXON Enterprises, Inc. from rice hulls contain a large fraction of particles in the sub 3.5μ m size range.

Environmental Impacts--

Air Quality--The air quality and solid waste disposal impact of carbon fiber use, the main subject of this study, is covered in Part II of this report.

Water Quality--There will be negligible impact on water quality from the manufacture, use and disposal of advanced composites. There is no direct use of water in the manufacture of any of the fibers identified, with the possible exception of alumina FP, where water is used to slurry alumina particles in the manufacturing process, in a manner which lends itself to total recycle. There will only be minor effluents from scrubbing towers used to remove vapor contaminants formed in the fiber manufacturing process. The impact of matrix manufacture will depend on the matrix. There is little water needed for prepreg or component manufacture other than for indirect cooling purposes.

The only impact that can be identified from the use of composites is a positive impact associated with the construction of water pollution equipment from advanced composites.

Noise--The use of advanced composites could significantly reduce industrial and environmental noise. First, the fabrication processes used to make advanced composites, particularly organic matrix composites, are less noisy than common fabrication processes used to make metal parts, such as forging and stamping. Secondly, the use of parts made of advanced composites in high speed machinery has resulted in noise reduction as a result of the high modulus and damping characteristics of advanced composites. Manufacture of items such as gears, gear housings and high speed moving parts out of advanced composites could result in a major reduction in factory noise level. Secondary effects that would accrue would be a lower industrial accident rate, less impairment of hearing of factory workers and a generally more comfortable work environment.

Product Safety and Reliability--

Product Reliability Issues--An important consideration in the use of new materials in structural applications is the ability to provide a long trouble-free life under the expected loading and environmental conditions. The user must be assured that the ultimate strength, load limit, fatigue characteristics and residual strength of these materials during the operational life of the structure are defined and well understood. A new structural technology must not contain any reliability or maintenance surprises. Unpredicted failures are known as accidents, and can result in economic losses, property damage, human injury and/or loss of life.

A significant fraction of past and current efforts of advanced composite technology has been devoted to obtaining a better understanding of the basic materials properties, to the development of test methods, to acquiring a statistically significant experimental data base for the establishment of safe and reasonable material allowables, to determining the effects of long-term environmental exposure on the properties of advanced composite materials in use and to the development of accurate design procedures and methods of structural analysis that take into consideration the nonisotropic properties of advanced composites.

The evolution of advanced composite technology has been accompanied by a signficant amount of conservatism and restraint on the part of potential users. With few exceptions, extensive testing and analysis has been performed before incorporation of an advanced composite structure in any aerospace operational system. Initial uses of advanced composites were limited to small parts not critical to the safety or integrity of the structural system. Advanced composite structures were then designed and utilized on a substitution basis as one-to-one replacements for metal structures, and which remained available as back-up systems. Structures that make extensive use of advanced composites are only now, after over fifteen years of experience, being considered seriously. During this evaluation there has been an extensive amount of continued testing, quality control and field evaluation. For example, the graphite-epoxy components of the Trident C-4 missile are radiographed numerous times during the course of their manufacture. Acceptance criteria are rigid throughout the production cycle. Materials, methods and procedures are closely scrutinized before they become qualified for use.

This philosophy has resulted in a slow and steady evolution and expansion of advanced composite technology, marred by relatively few accidents and surprises (such as, for example, the attack of polysulfone graphite composite spoilers by aircraft hydraulic fluids). The demands of this philosophy are patience and a large budget. An additional impact of this philosophy is that it has constrained the development and introduction of new technology. The certification cycle required to qualify a new material or manufacturing process tends to promote continued use of a previously certified material and process in new applications rather than using new or modified materials and methods that could be functionally more effective. The process is self reinforcing in that as more and more experience is gained with a given material and manufacturing method, the greater the level of confidence in that material and/or method, and the more likely its use will continue.

New product development has been limited to those materials that offer a major potential improvement in performance or cost reduction for established markets (e.g., polyimide matrix composites for military aircraft) or entry in new markets (e.g., unsaturated polyester matrix composites for automotive application).

Entry of advanced composites into new fields of application has been cautious as well, especially in that advanced composites are usually considered for use in highly stressed parts that are subjected to repetitive loads. A critical factor in the decision to use advanced composites instead of metals in a new application is the degree of confidence that the manufacturer has that the advanced composites will perform as expected. Competitive pressures often dictate that a new product be placed on the market within narrow constraints of price and time. Many potential applications of advanced composites cannot support extensive product development programs either in terms of costs or lead times and, in many instances, if sufficient design data and use experience are not readily available to the manufacturer, advanced composites will not be used even though potential benefits could accrue.

The major risks associated with the expanded use of advanced composites will be due to unforeseen degradation or environmental interaction of the advanced composite structure, the willingness of a manufacturer to gamble on the structural integrity of a product in a new application and human error.

Unforeseen factors represent the major risk in the use of advanced composites, with the greatest unknown being their long-term behavior and properties. There are very few advanced composite structures that have been in service for ten years or more. The validity of transposing data obtained under one set of use conditions to another is also an issue. This risk can be minimized by the development and application of improved nondestructive testing (NDT) techniques that could be applied in the field as part of a scheduled maintenance cycle.

The proliferation of product liability lawsuits in the past few years has made manufacturers very conservative in their introduction of new product technology. Since the total experience for advanced composites is significantly lower than for metals, a manufacturer already undertakes a higher perceived risk in simply using advanced composites instead of a more established material. As a result a manufacturer will tend to be more conservative in his use of advanced composites than in the comparable use of metals.

Human error is a factor that cannot be eliminated. An advanced composite structure could be improperly designed, manufactured, used or monitored, but so can metal or wood structures. The major difference between advanced composites and the more common materials of construction is that there are no generally accepted use codes for advanced composites, while universal specifications and standards exist for steel for example. In the aerospace industry these specifications vary with each of the major manufacturers, and moreover the requirements and specifications for advanced composites established by government agencies vary with the agency or with the application. There is a need for common design standards and product specifications that would be widely accepted as measures of good engineering practice.

Crashworthiness--The previous section considered the structural reliability and integrity of advanced composites within their design specifications. Another issue is the behavior of advanced composites when subjected to a high impact load as would occur in an automobile accident. Advanced composites, especially resin matrix composites, are inherently brittle materials that do not deform plasticly, whereas metals exhibit plastic deformation. The crashworthiness of current transportation vehicles is based on energy absorption by deformation of the metal structure. There are some questions as to the crashworthiness of advanced composite structures. If improperly designed, an advanced composite structure could shatter and fracture into sharp shards that would be an additional post-crash hazard to persons in or near the involved vehicles. However, there is also evidence to indicate that advanced composite structures can be designed to fail safely, and that crash energy can be absorbed by delamination of the composite or by fiber pull out. It has also been suggested that fiber composite structures would absorb a greater load elastically than a metal structure, so that low velocity impact damage would be less severe for an advanced composite structure than for a metal structure.

Flammability--Regulatory agencies and insurance companies are becoming increasingly concerned with the fire hazards of reinforced plastics, which can act as additional fuel and result in the generation of smoke, soot and toxic gases. The flammability of advanced composites is not signficantly different than the flammability of fiberglass reinforced plastics since flammability is a matrix-dependent characteristic. The degree of fire hazard will depend on the specific composition of the matrix rather than on the nature of the reinforcing fibers.

Reliability of Repaired Parts--The military services have been gathering service experience on advanced composite structures over the past ten years. Repair techniques for structural restoration of resin matrix composite aircraft structures with large area damage have been developed and experimentally validated. These methods have been used in the field and the repaired parts were found to be satisfactory for service. However, field maintenance personnel also used nonstandard techniques and several of these repairs were made so badly that they resulted in additional damage. In summary, with adequate training, repair instruction manuals and the proper materials and facilities, it should be possible to maintain and service advanced composite structures of increasing complexity.

Insurability of Advanced Composite Structures--The overall impact of all the above safety and reliability issues is an assessment of whether the use of advanced composites, or for that matter fiberglass reinforced structures, result in a greater hazard to society than metal structures. This is an assessment an insurance company has to make if it is to underwrite an insurance policy that is associated with a composite structure. The relative willingness of an insurance company to underwrite product liability insurance, as measured by the level of coverage and premiums, will be a measure of the perceived risk associated with composites. If this perceived risk is significantly higher than that perceived for metal structures, insurance may be higher or insurance may not be available at all, and could prevent diffusion of composites into consumer applications.

Enumeration of Specific Policies

The general policies described in the preceding paragraphs result from a number of different specific Congressional actions and regulations. These specific actions including appropriations, laws and regulations are listed below.

Appropriations--

1. Military Appropriations for the acquisition of new operational systems, as well as for the support of research and development activities.

2. NASA Appropriations for new systems acquisition and for the support of research and development.

3. Department of Energy Appropriations for the support of research and development activities related to improved energy generation systems (fusion reactors) and in energy conservation (fly wheels, electric vehicles).

4. Department of Transportation Appropriations for the support of research and development activities related to more energy efficient transportation vehicles.

5. Department of Commerce Appropriations to support the research activities of the National Bureau of Standards that are related to advanced composite structures.

6. National Science Foundation Appropriations to support research activities that are related to advanced composite structures.

Laws and Regulations--

1. Energy Policy and Conservation Act of December 22, 1975, and subsequent regulations of the NHTSA that pertain to the fuel economy characteristics of passenger automobiles.

2. Federal Motor Vehicle Safety Standards (49 CFR 571) and Federal Bumper Standards (49 CFR 581) which establish safety standards for passenger automobiles.

3. Federal Motor Carrier Safety Regulations (49 CRF 390-397) which establish safety standards for commercial vehicles used to carry passengers for hire and in interstate commerce.

4. Federal Aviation Regulations which establish safety standards for aircraft. These include Certification Procedures for Products and Parts (14 CRF 21); Airworthiness Standards for Normal, Utility and Acrobatic Aircraft (14 CRF 23), Transport Category Aircraft (14 CFR 25), Normal Category Rotorcraft (14 CFR 27), Transport Category Rotorcraft (14 CFR 29), Aircraft Engines (14 CFR 33), and Propellers (14 CFR 35), as well as Noise Standards (18 CFR 36).

5. Federal Freight Car Safety Standards (49 CFR 215) and the Railroad Safety Act (45 USC 435).

6. Coast Guard Vessel Certification and Inspection Regulations (46 CFR 201 et. seq., 40 CFR 24, 31, 71, 91, 176).

7. Noise Control Regulations such as Occupational Safety and Health Standards (29 CFR 1910), Subpart G: Occupational Health and Environmental Control, Section 1919.95 Occupational Noise Exposure; and EPA Noise Emission Standards for Construction Equipment (40 CFR 203).

8. Occupational Safety and Health Standards (29 CFR 1910), Subpart Z. Toxic and Hazardous Substances, insofar as they relate to health hazards associated with the materials used to make advanced composites.

9. Federal Fire Prevention and Control Act of 1974 (15 USC 2218).

10. Solid Waste Act of 1976 (43 USC 3251, Title II), Guidelines for the Thermal Processing of Solid Wastes (40 CFR 841), insofar as they apply to recycling or disposal of scrap advanced composite structures.

11. Federal Regulations Pertaining to Satellite Communications (47 CRF 25).

12. Economic Regulations of the Civil Aeronautics Board (14 CFR 200 et. seq.).

13. Air Pollution Regulations, such as Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines (40 CFR 85) and Control of Air Pollution from Aircraft (40 CFR 87), insofar as advanced composites reduce the need for large engines and reduce fuel consumption per mile traveled.

14. Federal Regulations concerned with the economic aspects of agricultural production, such as Federal Crop Insurance (7 CFR 401 et. seq.) Agricultural Conservation Programs (7 CFR 701 et. seq.), Farm Marketing Quotas and Acreage Allotements (7 CFR 711 et. seq.), Commodity Credit Corp. (7 CFR 1421) and Farmers Home Administration (7 CFR 1800 et. seq.).

15. Export Controls on Arms, Ammunition and Implements of War (15 CFR 370, Supplement 2). At the moment these regulations apply not only to military systems that contain advanced composite structures, but also to high performance filaments and prepregs.

16. Excise Taxes on Petroleum Fuels (26 CFR 4041, 4081, 4082).

SECTION 2

CONCLUSIONS

It is clear from the results of this study that there are a large number of current and potential applications for graphite composites in both consumer goods and industrial applications. In each application there is a particular set of technical and economic incentives that make the use of advanced composite materials advantageous over the use of the more traditional materials. In most cases the primary technical advantage of the composite is derived from its high strength-to-weight and stiffness-to-weight ratios. Corrosion-resistance and biocompatibility also provide technical incentives in some applications.

The economic incentives of composite materials vary from application to application. In all applications cost effectiveness is a factor. In determining whether or not to utilize a carbon fiber material, a potential manufacturer will set design specifications for the product. Then he will determine which materials can meet those criteria and, finally, which of the potential materials is least expensive. In some applications, however, this decision is made more complicated by the existence of applicable regulation or nonmonetary incentive structures.

In the sporting goods area graphite fiber is used to increase the stiffness or to lessen the weight of such items as skis, golf club shafts, tennis rackets and fishing poles. In these applications the manufacturer is motivated by incremental profits that can be made because the consumer believes that the graphite product is superior to the more traditional model. In two examples described in Section 3, it was determined that incremental profits amount to $38 and $26 on a graphite tennis racket and a pair of graphite ski poles respectively when compared with the use of more conventional materials in these products.

Graphite is attractive in a variety of other industrial and medical applications ranging from agricultural equipment and textile machinery to x ray tables and prosthetic devices. Economic incentives in these applications include straightforward cost-effectiveness benefits (e.g., textile picking sticks); increased agricultural production and decreased patient morbidity (e.g., implantable prosthetics).

The Energy Policy and Conservation Act of 1975 and subsequent federal regulations have set standards for production-weighted corporate average fuel economy until 1985. The penalty for noncompliance is $10 per automobile per mpg under the standard. Using lighter weight composite materials is one way to increase the fuel efficiency of automobiles. Currently, however, the price of graphite composites is too high to justify its use. However, as both fuel efficiency standards and fuel costs increase and the cost of graphite falls, this application may become economically feasible.

There are no fuel efficiency standards for the trucking industry, so economic incentives come from cost reductions. There are three possible types of benefits from the use of lightweight materials. The first is the reduced cost of production available through design simplification and reduced production energy requirements. Secondly, a lighter truck is more fuel efficient than a heavier one. Therefore, for trucks identical except for weight, the lighter one will realize fuel cost savings. Assuming travel of 120,000 miles per year and $1.40 per gallon of fuel, annual cost savings of $.24 per pound saved might be expected. If the truck is operated at the maximum gross combined vehicle weight, the tare weight reduction might be used to increase payload to either increase revenues (for-hire carriers) or decrease operating costs (private carriers). If graphite leaf springs are used, saving 272 pounds, increased pretax profits might be in the range of $100 to $800 per truck depending on the type of operation. (See Section 4 for more detail.)

Similarly in the aerospace industry, the benefits of carbon fiber composites are due to their physical and thermal properties. Improved performance characteristics are load carrying capability, fracture toughness, flame ignition resistance and reduction in weight, leading to fuel savings. If graphite sidewalls, partitions, ceilings and stowage bins are used in a Boeing 767 instead of fiberglass, savings of approximately 143 pounds are made per aircraft. Assuming an average trip of 1,000 miles, a total distance traveled per year of 1.2 million miles and a fleet of 1,383 three-engine 767s by 1990, the estimated savings for the lifetime of the fleet is $60 million (see Section 4 for more details).

The potential economic impact of the disposal of these products containing carbon fiber through both the municipal and the industrial solid waste stream was the major focus of this study. Since the municipal solid waste stream is composed of refuse from residences, commercial establishments and institutions, only the following applications are most likely to enter it:

- Sporting goods
- Recording instruments
- Telescopes and binoculars
- Tripods
- Cameras.

The remaining applications can be expected to enter the industrial waste stream:

- Aerospace applications
- Automotive applications
- Applications in the trucking industry
- Industrial machinery
- Material handling equipment
- Chemical plant structures and equipment
- Agricultural machinery.

There are three potential economic impacts of fiber release in the disposal of consumer goods containing carbon fiber in the municipal waste stream. These are:

- Health effects
- Electrical failures
- Mechanical impact.

The potential health effects from fiber release may include skin, upper respiratory and eye irritations. If there is a great deal of fiber breakdown during processing and incineration, fiber particles could also enter the lungs. While it is presently believed that the fibers are noncarcinogenic, the potential health effects cannot be analyzed at this time because neither animal tests nor human exposure data collection have been completed to determine the actual biological impacts of fiber ingestion by humans. Without such test results, the biological impact of carbon fiber release will remain uncertain for many years.

The mechanical impacts, such as clogging air filters, are likely to be insignificant. The economic impacts due to electrical failures associated with carbon fiber disposal arise when fibers are emitted into the air and enter electrical equipment, resulting in electrical shorts and equipment failures. The magnitude of these impacts will be determined by the amount of fibers released when disposing of carbon fiber composite material. The principal release mechanism is through fiber entrainment in incinerator stack gases. The amount of entrainment is affected by the type of incinerator, as well as the efficiency of the unit's pollution control equipment.

It is estimated that about 600,000 kg (1,319,200 pounds) of carbon fiber will enter the municipal solid waste stream, while approximately 7,200,000 kg (15,840,000 pounds) will enter the post-1990 industrial solid waste stream. This material will be landfilled, incineratred or unmanaged.

Currently 89 percent of the municipal solid waste in the United States is landfilled, 6 percent is recycled, 4 percent incinerated without heat recovery and 1 percent is incinerated for energy recovery. A generously high estimate was made that 0.5 percent of carbon fiber in the industrial solid waste stream is incinerated (the remaining 99.5 percent is landfilled), based on a survey of major manufacturers and users of carbon fiber.

The annual economic loss resulting from the incineration of consumer goods containing carbon fiber material in the municipal solid waste stream is negligible. The economic impact of carbon fiber release from shredder explosions and landfill fires is also determined to be insignificant.

The annual economic impact for the nation resulting from the incineration of carbon fiber materials is insignificant. Even in the highly improbable, worst-case scenario - incineration of all carbon fiber in the industrial waste stream - the impact is small compared to the benefits of carbon fiber use.

SECTION 3

CONSUMER GOOD APPLICATIONS

GOLF SHAFTS

The Application

The manufacture of the golf club shaft was the first high-volume use of graphite in the commercial sector. Manufacturers and other proponents of the graphite shaft claim that because of graphite's high strength-to-weight and stiffness-to-weight ratios, it offers the golfer a number of advantages. The largest advantage attributable to the use of graphite is a shift in the balance point of the club toward the head, which is possible because of the lighter shaft. This is said to allow an easier swing and greater clubhead acceleration which leads to a more powerful stroke. This greater power means longer distance.

In addition, some manufacturers of graphite shafts claim that because of the advances in engineering possible with graphite, as well as the physical properties of the material, it is possible to produce a club that also provides greater accuracy. The claim is that the torque or thrust at impact with the ball can be reduced, thus the ball can be hit more squarely, giving greater accuracy to the shot.

Finally, manufacturers claim that graphite can give uniform weights across all flexes, a uniform flex pattern (a club with a uniform flex pattern will produce a uniform curve when bent between both ends) and durability.

A number of companies have been working with graphite shafts since the late 1960s. The greatest increase in the sales of graphite shafts came during the period from 1973 to 1975. This boom followed the predictable fad cycle. In 1973 the graphite shaft became widely accepted on the professional touring circuit. In the next few years sales boomed, first in graphite shafts for woods and then later for irons as well. While graphite provides the same advantages for irons as for woods, the cost of the graphite shaft remained very high relative to the normally low-priced irons.

Since 1975 the industry has matured. Initially slowdowns in sales were attributed to the general economic downturn. Further, manufacturers of steel, aluminum and fiberglass shafts have responded to the competition of graphite shafts by improving their products and recapturing sales. Within the last two years the graphite shaft has seemingly lost popularity. The claims against the graphite shaft are that it does not offer the same flex as the steel shaft and, therefore, some do not feel that it is as playable. The cost of the graphite shafts has remained very high relative to the cost of more traditional materials. Others claim that the value of the relative "lightness" of the shaft is limited as further reduction in weight destroys the feel of the club.

Finally, some golf pros sense a bit of consumer resistance to the black color of the graphite shafts.

Traditional materials for golf shaft production include steel, aluminum and fiberglass. Hollow steel tubes that have been extruded or treated by stretching under heat to form the tapered shaft have traditionally been the leading type of shafts. Aluminum shafts, like graphite, experienced a "fad-like" growth in sales in the late 1960s and early 1970s. These shafts are produced much as the steel shafts are. A few training shafts are made of fiberglass. The manufacturer of fiberglass will generally buy fiberglass prepreg. The prepreg is then cut into blanks, rolled on a mandrel then wrapped in cellophane for curing. After curing, the mandrel and cellophane are removed and the shaft is sanded.

The process just described for the production of fiberglass shafts is very similar to that used in the making of a large number of the graphite clubs on the market today.

At least one other process for making graphite shafts is in use commercially today. Plies of 100 percent graphite fibers are wrapped around a tapered mandrel. These are then bonded with epoxy under heat and pressure. This process is used by Babcock & Wilcox who claim that it produces a dense, more consistent structure than the process that uses prepreg blanks as described above [6].

The Economic Incentives

In estimating the economic incentive to produce graphite golf shafts, the manufacturer must look at the entire market for golf clubs in both the domestic and export markets. In 1978 U.S. consumers purchased 9,130,000 individual clubs for a total of more than $200 million. While this seems a sizeable market, it, in fact, represents a decline from recent years. Table 1 shows the volume and dollar value of consumer purchases from 1973 to 1978.

Statistics indicate that relative to most other (nonvehicular) sports, golf is a sport of the affluent. In 1978, 37.3 percent of clubs sold were bought by individuals with annual family incomes of $25,000 and over. Only 9.6 percent of the clubs were bought in families of under $10,000 income per year [6].

Furthermore, a large percentage of clubs were bought at sports specialty and pro shops. Table 2 shows the 1978 consumer purchases of golf club sets by type of establishment, where purchased and the average price per set associated with these purchases. The overall average price of a golf club purchased in the United States in 1978 was $21.98. The geographic distribution of 1978 consumer purchases of golf clubs is shown in Table 3.* This follows a trend that might be expected from population figures and climatic variation, with the East North Central and Middle Atlantic regions leading in purchases and the Mountain and South East Central purchasing least. It seems likely that the nature and composition of the existing market for relatively expensive golf equipment was a factor in the early acceptance of the high-priced graphite clubs.

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*The nine regions listed correspond to the Census Divisions utilized by the U.S. Department of Commerce.

TABLE 1 CONSUMER PURCHASES OF GOLF CLUBS, 1973-1978, IN MILLIONS

YEAR	NUMBER OF CLUBS	DOLLAR VALUE
1973	13.2	220.0
1974	13.2	228.1
1975	12.2	225.4
1976	12.1	239.6
1977	11.0	236.2
1978	9.1	200.7

SOURCE: THE SPORTING GOODS MARKET IN 1979, PREPARED FOR THE NATIONAL SPORTING GOODS ASSOCIATION BY IRWIN BROH & ASSOCIATES, INC., DES PLAINES, ILLINOIS, 1979, P. 44.

TABLE 2 CONSUMER PURCHASES OF GOLF CLUB SETS IN 1978 BY PLACE OF PURCHASE

PLACE OF PURCHASE	PERCENT OF UNITS	AVERAGE PRICE, $
GENERAL SPORTING GOODS	13.6	149.00
SPORTS SPECIALTY & PRO SHOPS	43.8	220.46
DEPARTMENT STORES	7.6	96.59
DISCOUNT STORES	13.3	83.04
CATALOGS	4.2	-
OTHER OUTLETS	14.1	103.06
UNKNOWN	3.4	-

SOURCE: THE SPORTING GOODS MARKET IN 1979, PREPARED FOR THE NATIONAL SPORTING GOODS ASSOCIATION BY IRWIN BROH & ASSOCIATES, INC., DES PLAINES, ILLINOIS, 1979, P. 44.

TABLE 3 GEOGRAPHIC DISTRIBUTION OF 1978 CONSUMER DOLLAR PURCHASES OF GOLF CLUBS

GEOGRAPHIC REGION	PERCENT OF TOTAL
NEW ENGLAND	4.3%
MIDDLE ATLANTIC	17.3
EAST NORTH CENTRAL	30.6
WEST NORTH CENTRAL	7.7
SOUTH ATLANTIC	13.2
EAST SOUTH CENTRAL	2.7
WEST SOUTH CENTRAL	7.1
MOUNTAIN	4.5
PACIFIC	12.6
TOTAL	100.0%

SOURCE: THE SPORTING GOODS MARKET IN 1979, PREPARED FOR THE NATIONAL SPORTING GOODS ASSOCIATION BY IRWIN BROH & ASSOCIATES, INC., DES PLAINES, ILLINOIS, 1979, P. 46.

The major manufacturers of graphite golf clubs include [7]:

- Aldila
- Babcock & Wilcox
- Carbonite (3M)
- Graftek Leisure Products (Exxon)
- Graphite Technology
- Lamiglas
- Research Engineering Corp.
- Shakespeare/Columbia
- Skyline Industries.

Grafalloy and possibly others also make some golf club shafts.

The shafts manufactured by those listed above are sold either directly by the manufacturer or through a large number of wholesalers, distributors and retailers of golf shafts and clubs. The markup or difference between the production cost and the retail price will, as in all consumer markets, be somewhat dependent on the number of suppliers (or middlemen) handling the product. These price markups are compensation for the overhead, handling and advertising costs of each of the suppliers as well as the profit that is accrued at each level.

Assuming that the overhead, handling, packaging and advertising costs of all clubs are the same, retail price differences between different clubs is then the sum of the differences in manufacturing costs and the differences in profits. There is no reason to believe that a club with a graphite shaft is more expensive to handle than one with a steel or fiberglass shaft. However, there may be some small differential advertising expenses associated with a particular promotional effort. These promotions will vary with the individual manufacturers and retailers and are not necessarily specific to graphite shafts. These differences are therefore believed to be negligible at the overall industry level. Thus, comparing the differences in manufacturing costs and retail prices of a graphite shaft and a shaft made of a more traditional material will determine the additional profit attributable to the use of that graphite shaft. These incremental profits will be divided among all the suppliers of the shafts or clubs from the manufacturers to the retailers. Without additional (proprietary) information it is impossible to determine the distribution of these increased profits. In total, however, the distribution is unimportant because the economic incentive for each of the suppliers to sell more graphite shafts comes from the relatively higher profits he gains from such sales.

The following paragraphs present the manufacturing costs of a graphite shaft made from carbon fiber/epoxy prepreg. Table 4 lists the operations in the graphite manufacturing process as well as the equipment required and the estimated purchased equipment cost. Table 5 presents the manpower commitment for each of these operations.

The following cost estimates were provided by Robert Kaiser of Argos Associates, Inc. in a letter to Peter Stevenson, Econ, Inc., February 8, 1980. Cost estimates assume a production rate of 120 shafts per hour, one eight-hour shift per day, five days per week and 50 weeks production per year. Thus the annual production equivalent is 240,000 shafts per year. Assuming that 15,000 shafts of each type are rejected each year, the net annual production is 225,000 shafts per year.

TABLE 4 OPERATIONS IN GRAPHITE GOLF SHAFT MANUFACTURE AND EQUIPMENT COST

OPERATION	REQUIRED EQUIPMENT	ESTIMATED PURCHASED EQUIPMENT COST, $
1. PREPREG RECEIVING	DOLLY LIFT TRUCK	1,500
2. PREPREG STORAGE	WALK-IN REFRIGERATOR-24' X 5' X 8' = 960 FT^3	30,000
3. REMOVAL OF PREPREG FROM STORAGE	DOLLY LIFT TRUCK	1,500
4. CUT PREPREG TO LENGTHS	M1500 AUTOMATIC CUTTER	3,000
	WORK BENCH 4' X10'	200
5. CUT PATTERNED SHEETS	M5200 CUTTER	3,000
	WORK TABLE 5' X 10'	200
6. PATTERN STORAGE	SHELVING	1,500
7. PATTERN TRANSFER	PATTERN CARTS, 3 EA.	900
8. BLANK PREPARATION	WORK BENCHES, 2' X 12', 2 EA	300
9. ROLLING OPERATION	FEEDER TABLE, 4' X 12'	200
	M8008 ROLLING TABLE, 6'	7,300
10. CELLOPHANE WRAPPING	M2400 CELLOPHANE WRAPPER & 2 FEED TABLES	6,000
11. CURING	OVEN CARTS, 5' X 5' X 5', 3 EA.	3,000
	OVEN, CURING, 6' X 6' X6' = 216 FT^3 @ \$150/FT^3	32,000
12. MANDREL REMOVAL	M2100B MANDREL PULLER	4,000
13. BLANK TRANSFER	TRANSFER CARTS, 2 EA., 1.5' X 12'	800
14. CELLOPHANE REMOVAL	M2200 CELLOPHANE REMOVER	5,400
	WORKBENCH, 3' X 12'	200
	CONVEYOR	1,200
15. SANDING	M2000 SANDER	3,000
	CONVEYOR	1,200
	TRANSFER CART, 2 EA.	800
SUBTOTAL		104,400
OFF-LINE OPERATIONS	**REQUIRED EQUIPMENT**	**ESTIMATED PURCHASED EQUIPMENT COST, $**
A. MANDREL STORAGE	STORAGE CRIB	700
	MANDRELS, 3600 EA. @ \$6 PER MANDREL	21,600
B. MANDREL TRANSFER	TRANSFER CARTS, 6 EA. FOR ALL OPERATIONS	2,400
C. MANDREL CLEANING AND PREP.	M2600 CLEANER WITH TANK	
	RESIN TANK	6,000
	DIP TANK	
D. WASTE DISPOSAL	GARBAGE CANS, DUMPSTER	600
SUBTOTAL		31,300
SUBTOTAL FROM ABOVE		104,400
TOTAL PURCHASED EQUIPMENT		135,700
	EQUIPMENT REQUIRING INSTALLATION	100,600
	LESS REFRIGERATOR AND OVEN WHICH ARE INSTALLED COST ESTIMATES	62,000
	EQUIPMENT TO BE INSTALLED	38,600

SOURCE: ROBERT KAISER, LETTER TO MR. PETER STEVENSON, ECON, INC., DECEMBER 17, 1979.

TABLE 5 OPERATIONS IN GRAPHITE GOLF SHAFT MANUFACTURE WITH ASSOCIATED MANPOWER REQUIREMENTS

OPERATION	MANPOWER REQUIREMENTS
1. PREPREG RECEIVING (GENERAL ASST)	1
2. PREPREG STORAGE	
3. REMOVAL OF PREPREG FROM STORAGE	
4. CUT PREPREG TO LENGTHS	
5. CUT PATTERNED SHEETS	1
6. PATTERN STORAGE	
7. PATTERN TRANSFER	
8. BLANK PREPARATION	2
9. ROLLING OPERATION	1
10. CELLOPHANE WRAPPING	1
11. CURING	
12. MANDREL REMOVAL	1
13. BLANK TRANSFER	
14. CELLOPHANE REMOVAL	1
15. SANDING	1
SUBTOTAL	9
OFF-LINE OPERATIONS	
A. MANDREL STORAGE	
B. MANDREL TRANSFER	
C. MANDREL CLEANING AND PREP.	2
D. WASTE DISPOSAL	PERF. BY GEN. ASST.
SUBTOTAL	2
TOTAL DIRECT LABOR	11
FOREMAN	1

SOURCE: ROBERT KAISER, LETTER TO MR. PETER STEVENSON, ECON, INC., DECEMBER 17, 1979.

The operating costs listed here apply to the production of graphite golf shafts. Each finished shaft is assumed to weigh 73 grams. The material used is Fiberite HY-E-1040 A1E which is a T-300 graphite fiber in a 250° F cure epoxy resin. Prices quoted by Fiberite on February 6, 1980 are as follows:

Quantity	200 lbs (91 kg)	200-500 lbs (91-227 kg)	500 lbs (227 kg)
Price $/lb	32.48	31.88	30.40
Price $/kg	71.46	70.14	66.88

Note that 3M quotes a price for its Thornel 300 in 250° F resin (SP288) at $120 per pound ($264 per kg) but they are believed to do relatively little graphite business.

TENNIS RACKETS

The Application

The use of graphite in the construction of tennis rackets and other sports rackets has developed much more recently than in golf clubs. In racket materials there is a trade-off between characteristics that improve control and those that improve power. Generally speaking, a very flexible racket increases the power of a player's stroke but diminishes the control. The vibration that a racket transmits to the player's arm is also an important characteristic. Hits that are off-center on the racket set up vibrations. If these vibrations are not damped, they are transmitted to the player's arm and can cause jolting and even elbow injury. An extremely stiff racket will tend to pass these vibrations into the arm while a racket made of "softer" material will be more absorbent. The final characteristics of all tennis rackets that are affected by the use of graphite in construction are weight and "playability." A racket that is too heavy will tire and possibly strain arm muscles while a racket that is too light will cause the player to use too much wrist motion in his strokes.

The playability of the racket is essentially the feel of the racket as it moves through the air. This is affected by the wind resistance (determined by the shape of the frame construction), its weight and its balance (relative weight of the head to the shaft).

Because of its very high strength-to-weight and stiffness-to-weight ratios, graphite, when used in the construction of rackets, is able to affect each of the general characteristics mentioned above. Because of its strength, a racket including graphite fibers can be much stiffer and at the same time lighter than a similar racket using competing materials. Since there are many different levels and types of players, each requiring different characteristics in a racket, graphite fibers are used in combination with many different materials in racket construction. Thus rackets that incorporate some graphite fibers can cover virtually the entire spectrum of needs. In attaining this variety, rackets are constructed using just a few graphite fibers as inlays around the head or in the shaft, as overlays at the throat or shoulder, or graphite fibers can be used in an epoxy composite for 100 percent of the frame construction. In general, however, manufacturers claim that a graphite racket:

- Has an enlarged "sweet spot"
- Retains its strength and stiffness over a longer lifetime
- Provides a better balance
- Delivers greater maneuverability.

In the few years since graphite rackets first appeared on the market, a great number of advances have been made in construction techniques. Rackets containing graphite that are available in the United States are listed in Table 6. Note that they include combinations with fiberglass, wood, Kevlar and polyurethane foam. Those listed as "100 percent graphite" are actually composites of graphite fibers and a resin matrix. This matrix is generally thermosetting (usually epoxy) but some thermoplastics are also used [8].

Because of the great variation of the amounts and functions of the graphite fibers used in rackets, there is naturally a wide range of techniques used in construction. Many of the rackets that are either entirely graphite-reinforced plastic or another combination of laminated materials use graphite prepreg. The materials are cut to size, then packed in molds. These molds are placed in special ovens for heat and pressure processing. The rackets are then removed from the molds, cleaned, painted and finished with grip pallets, grips and cosmetics. The other popular technique for composite graphite racket construction begins with a traditional, usually wood, racket. A small groove is cut in the head and/or shaft of the frame and fibers are inlaid. Generally epoxy holds the fibers in place. Later additional overlays are attached and the cosmetics and grip are added.

The more traditional materials for tennis racket construction are:

- Wood
- Aluminum
- Steel
- Fiberglass.

The other new materials for tennis rackets, besides graphite, are boron and Kevlar. These materials also have high strength-to-weight and stiffness-to-weight ratios and, therefore, are used for many of the same reasons that graphite is used.

Because wood is a natural material, its strength and weight properties vary with the type and individual piece of wood selected. In racket construction wood has a few drawbacks, namely, no two rackets respond identically, it is relatively heavy and it is relatively short-lived, especially when used in heavy play or if it receives improper care. All wood rackets are made by laminating strips of (generally) several different types of wood. Excess glue is removed and rackets sliced to the appropriate thickness. Reinforcing strips and overlays are applied before string holes are countersunk and beveled. After this, hand pallets are added and the racket is sanded, ready for testing, cosmetics and grip.

Aluminum rackets are actually made of aluminum alloyed with other materials. The usual combinations are aluminum with silicon, magnesium, copper and chromium or zinc, magnesium, copper and chromium. The most common aluminum alloys used in tennis racket construction are 6061, 7005 and 7075. 6061 contains silicon and is tempered to various degrees of hardness. 7005 and 7075 contain zinc and are stronger and stiffer than 6061 with 7075 being the strongest [9]. The most common ways of manufacturing the aluminum racket are by extruding or pultruding. In extrusion, the aluminum is melted and pushed through a die to give it specific shape. In pultrusion a preformed piece of alloy is pulled through a die. This latter process is generally only used on the harder alloys. After the frame shape is created, string

TABLE 6 GRAPHITE TENNIS RACKETS AVAILABLE IN U.S. RETAIL MARKET, 1979

RACKET	CONSTRUCTION	RETAIL DISTRIBUTOR
LEGEND	FIBERGLASS/GRAPHITE TUBE	AMF HEAD DIVISION
HEAD VILAS	GRAPHITE LAMINATIONS	AMF HEAD DIVISION
ROSSIGNOL C-12	ONE GRAPHITE LAMINATION	ROSSIGNOL SKI COMPANY
CANNON	100% CONTINUOUS GRAPHITE FIBER	ALDILA INC.
GEMINI	100% CONTINUOUS GRAPHITE FIBER	ALDILA INC.
ULTRA/PWS	100% GRAPHITE, BRAIDED TUBE	WILSON SPORTING GOODS COMPANY
CARBONE	100% CARBON FIBER	DONNAY USA CORPORATION
CARBONGLAS	50% CARBON/50% FIBER	DONNAY USA CORPORATION
GRAPHITE/WOOD	GRAPHITE SHOULDER OVERLAY	DONNAY USA CORPORATION
PRINCE GRAPHITE 110	100% GRAPHITE	PRINCE MANUFACTURING INC.
CARBONEX 8	TWO CONTINUOUS FILAMENT BRAID GRAPHITE AND TUBES WITH 3-PLIES FIBERGLASS	YONEX INC.
CARBONEX 7	ONE GRAPHITE BRAIDED TUBE WITH 4-PLIES FIBERGLASS	YONEX INC.
CARBONEX 1	COMPOSITE WOOD, FG AND CF	YONEX INC.
GRAPHITE RULER	WOVEN GRAPHITE (HOLLOW)	KAWASAKI (CURLEY-BATES COMPANY)
GRAPHITE RULERFLEX	WOVEN GRAPHITE (HOLLOW)	KAWASAKI (CURLEY-BATES COMPANY)
GRAPHITE CP001	WOVEN GRAPHITE AT KEY STRESS POINTS	KAWASAKI (CURLEY-BATES COMPANY)
FIBERGRAPH	GRAPHITE OVERLAY	PDP SPORTS COMPANY
ADS 775, GRAND PRIX	70% GRAPHITE/30% FIBERGLASS	ADIDAS USA
ADS 070, VIVANTE	CARBON GRAPHITE LAMINATIONS	ADIDAS USA
YAMAHA YFG 70	GRAPHITE AND FIBERGLASS	YAMAHA INTERNATIONAL CORPORATION
YAMAHA YFG 50	GRAPHITE REINFORCED	YAMAHA INTERNATIONAL CORPORATION
DUNLOP GRAPHITE FRAME	GRAPHITE	DUNLOP SPORTS COMPANY
PHANTOM II	100% GRAPHITE TUBES (OVERSIZED HEAD)	SLAZENGERS INC.
PHANTOM GRAPHITE	100% GRAPHITE TUBES	SLAZENGERS INC.
GRAPHITE CHALLENGE	GRAPHITE REINFORCED THROAT	SLAZENGERS INC.
TRABERT, C-6 GRAPHITE	ONE PIECE MOLDED GRAPHITE/EPOXY	TONY TRABERT (PROGROUP INC.)
TRABERT, BIG BUBBA	ONE PIECE MOLDED GRAPHITE/EPOXY	TONY TRABERT (PROGROUP INC.)
SCEPTER X-L	SOLID GRAPHITE AND KEVLAR, UNIFRAME	SCEPTER (GRAPHITE MASTER INC.)
SCEPTER	SOLID GRAPHITE AND KEVLAR, UNIFRAME	SCEPTER (GRAPHITE MASTER INC.)
WORLD STAR PRO	FIBERGLASS, GRAPHITE REINFORCED DOUBLE CHAMBER	KNEISSL OF AMERICA
WORLD STAR COMP	FIBERGLASS, GRAPHITE REINFORCED DOUBLE CHAMBER	KNEISSL OF AMERICA
SCORPION GRAPHITE	GRAPHITE FIBER, OPEN THROAT	BANCROFT SPORTING GOODS COMPANY
BLACK ACE	GRAPHITE FIBER POLYURETHANE FOAM FILLED	PRO KENNEX (KENNEX SPORT CORPORATION)
GRAPOWER 80	GRAPHITE AND WOOD COMPOSITE	PRO KENNEX (KENNEX SPORT CORPORATION)
GRAPOWER 70	GRAPHITE AND WOOD COMPOSITE OPEN THROAT	PRO KENNEX (KENNEX SPORT CORPORATION)
GRAPHITE COMPOSITE	GRAPHITE BRAID WITH WOOD & FIBERGLASS	SNAUWAERT NORTH AMERICA
BORONITE	BORON STRIP, GRAPHITE OVERLAY WOOD/ FIBER CORE	SNAUWAERT NORTH AMERICA
BORONITE TWO	BORON STRIP, GRAPHITE OVERLAY WOOD/ FIBER CORE	SNAUWAERT NORTH AMERICA
FIBER COMPOSITE	WOOD CORE, FIBERGLAS GRAPHITE OVERLAY	SNAUWAERT NORTH AMERICA

SOURCE: TENNIS DIRECTORY, FALL 1979, SKI-EARTH PUBLICATIONS, BOSTON, PP. 30-58.

holes are drilled, other parts such as a throat piece are riveted in place, foam and plastic grip parts and string strips are added and the grip is wrapped.

Steel rackets are also alloys. They include iron, carbon and other materials. Steel's only drawback in racket construction is that it is very heavy. It is approximately three times as heavy as aluminum and five times as heavy as graphite. To compensate for the weight of the material, most steel rackets are constructed from hollow crushed tubing. Steel rackets first became popular with the introduction of the Wilson T-2000 in the late 1960s. Even though it is strongly rivaled by the new aluminum frames it remains a fairly popular choice.

Fiberglass is another fairly recent addition to the list of tennis racket materials. The fiberglass parts are cut and placed in a mold. Sometimes an air bladder is inserted for internal pressure during molding. The pallet and wedges forming the throat shape can be added before the mold enters the oven for heat and pressure. After the molds are removed rackets are cleaned, grip bases and grips are added.

The Economic Incentives

As in the other consumer-oriented industries, the producer's incentive to manufacture and sell a product depends on the profit that he is able to earn. Furthermore, since a racket made of one material is completely substitutable for a racket of a different material based on the purchaser's desires, the manufacturer of graphite rackets must consider the industry as a whole. In 1978 U.S. consumers spent $137 million to purchase 4,900,000 tennis rackets [10]. As in many other sporting goods areas, this figure represents a sizeable (41 percent) decline from the 1977 figure. Consumer purchases of tennis rackets over the period 1973 to 1978 are shown in Table 7. While the 1978 figure does represent a large fluctuation, it is believed to be at least in part due to overall economic conditions and the over saturation of the market in recent years. This decline is not believed to indicate a change in the general popularity of tennis. Furthermore the decline in sales seems to have hit the sales of lower quality rackets most heavily [11].

Purchases of tennis rackets were reasonably evenly distributed across geographic regions and family income levels. Table 8 shows the geographic distribution and Table 9 presents the distribution of the annual family income of tennis racket purchasers.

Just over 40 percent of racket purchases in 1978 were made in sports stores or pro shops, while 46 percent were made in discount or department stores [11]. The remaining rackets were bought from catalog or other outlets or their origin is unknown.

While the average price of the tennis rackets bought in the United States in 1978 was about $28, there is substantial variation in the price based on the materials used and the quality of workmanship of the rackets. Table 10 shows the distribution of model types available to the U.S. consumer. Prices listed are the suggested retail price and do not reflect any discounting that may occur. The price of the average model is the arithmetic average of the prices found within the construction category. It is not a weighted average of the purchases made.

TABLE 7 U.S. CONSUMER PURCHASES OF TENNIS RACKETS FOR 1973 TO 1978 (IN MILLIONS)

YEAR	NUMBER OF RACKETS (MILLIONS)	DOLLAR VALUE (MILLIONS)
1973	6.2	93.1
1974	8.5	144.2
1975	9.2	181.5
1976	8.6	183.7
1977	8.3	174.7
1978	4.9	137.0

SOURCE: THE SPORTING GOODS MARKET IN 1979, PREPARED FOR THE NATIONAL SPORTING GOODS ASSOCIATION BY IRWIN BROH & ASSOCIATES, INC. DES PLAINES, ILLINOIS, P. 70.

TABLE 8 GEOGRAPHIC DISTRIBUTION OF 1978 CONSUMER PURCHASES OF TENNIS RACKETS

GEOGRAPHIC REGION	DISTRIBUTION (PERCENT)
NEW ENGLAND	6.5%
MIDDLE ATLANTIC	17.5
EAST NORTH CENTRAL	17.4
WEST NORTH CENTRAL	8.7
SOUTH ATLANTIC	16.3
EAST SOUTH CENTRAL	5.4
WEST SOUTH CENTRAL	9.0
MOUNTAIN	6.2
PACIFIC	13.0
TOTAL	100.0%

SOURCE: THE SPORTING GOODS MARKET IN 1979, PREPARED FOR THE NATIONAL SPORTING GOODS ASSOCIATION BY IRWIN BROH & ASSOCIATES, INC., DES PLAINES ILLINOIS, P. 72.

TABLE 9 DISTRIBUTUION OF 1978 CONSUMER PURCHASES OF TENNIS RACKETS BY ANNUAL FAMILY INCOME

ANNUAL FAMILY INCOME	DISTRIBUTION (PERCENT)
UNDER $10,000	14.9%
$10,000 - $14,999	23.4
$15,000 - $19,999	14.4
$20,000 - $24,999	14.8
$25,000 & OVER	32.5
TOTAL	100.0%

SOURCE: THE SPORTING GOODS MARKET IN 1979, PREPARED FOR THE NATIONAL SPORTING GOODS ASSOCIATION BY IRWIN BROH & ASSOCIATES, INC., DES PLAINES, ILLINOIS, P. 72.

TABLE 10 TENNIS RACKET MODELS AVAILABLE FROM RETAILERS IN THE UNITED STATES, 1979

CLASS NUMBER	CONSTRUCTION	RANGE OF PRICE LOW $	RANGE OF PRICE HIGH $	NUMBER OF MODELS IN CLASS	PRICE OF "AVERAGE MODEL" $
1	100% CF	89	250	12	185
2	100% FG	40	100	11	72
3	WOOD	20	98	20	45
4	ALUMINUM	30	95	30	62
5	WOOD/FG	30	106	10	75
6	CF/FG	75	175	11	123
7	CF/KEVLAR	165	230	4	203
8	WOOD/CF OVERLAY	37	100	10	77
9	WOOD/AL OVERLAY	114	114	1	114
10	STEEL	56	72	5	63
11	AL/FG	56	90	3	75
12	WOOD AND BORON (FG)	68	125	6	85
13	KEVLAR AND FG	100	160	2	130
14	WOOD/CF/FG	140	140	2	107
15	WOOD AND FIBER	20	98	28	54

CF-CARBON FIBER
FG-FIBERGLASS
AL-ALUMINUM

SOURCE: TENNIS DIRECTORY, FALL 1979, SKI-EARTH PUBLICATIONS, BOSTON, MA PP. 30-58.

While there are many retailers of graphite rackets in the United States, the list of manufacturers is much smaller. Often ghost companies produce rackets that are sold under other brand names. Many of the rackets which are sold in this country are either imported or are made by the following manufacturers:

- Aldila
- Babcock & Wilcox
- Exxon/Graftex Leisure Products
- Grafalloy Corp.
- Tremont Research Co. [12]

The use of graphite in tennis rackets is probably still in a fad stage in which consumers are purchasing the rackets as much for prestige as for performance. Even so, graphite seems to offer enough real advantages that continued growth in its acceptance is projected. The economic incentive to continue to produce these rackets comes from their relative profitability. While this incentive will probably decrease until the market becomes mature or stable, it will continue to exist. This change in the character of the market is evidenced by the recent introduction of a few graphite-containing rackets at substantially reduced costs. The following example shows the current economic incentives to sell graphite rackets. The additional profit is distributed among those who manufacture the rackets and those who sell them. In part this profit is also used to recover research and development costs.

Because the fabrication processes of rackets that are 100 percent graphite/epoxy or 100 percent fiberglass/epoxy are virtually identical, construction of a racket of each type will be considered. The graphite prepreg used is assumed to be about 60 to 65 percent fiber by volume and somewhat higher by weight. The fiber is 6,000 ton, 30 mil. modulus in a 250° F resin, specific gravity 1.57. The current price of this material is approximately \$31 per pound [13].

The fiberglass is assumed to be E-Glass in an epoxy resin. It is 53 percent fiber by weight, specific gravity 1.88. The current price is about \$8 per pound [13].

In both rackets the material is cut and placed in a two-piece mold. The labor, capital and other associated costs exclusive of material in each case are the same and, therefore, do not affect the relative profitability of each type of racket. The material costs, however, do vary substantially. Finished tennis rackets weigh from about 12 ounces to as much as 16 ounces. Assuming these example rackets are to be of equal medium weights, the frames without the grip base, grip and pallets will weigh about 12 ounces. A prepreg scrappage rate of about 25 percent is assumed. Therefore the material for the fiberglass frame will be

$$\$8/\text{lb}(.75\ \text{lb})(1.00 + .25) = \$7.50 \text{ per racket.}$$

The corresponding graphite material cost is \$29.06. Thus the difference in materials cost is \$21.56.

The two molds are then put in pressurized ovens where the heat and pressure are equal. Once again the costs are equal and do not affect the profitability. The same grip base and grip pallets are attached and identical grips are wrapped. While the cosmetic paint and decals may differ, the costs of such are assumed to be approximately equal. Therefore the only significant cost difference between the two rackets is the material cost difference. The graphite racket costs about $22 more to produce than the fiberglass racket.

In the retail market, however, the price of the two rackets is likely to be substantially different. As an example, one firm markets nearly identical rackets, one of which is graphite/epoxy and the other is fiberglass/epoxy. The suggested retail price of the graphite racket is $159 while the fiberglass racket sells for $99. With the production cost difference of $22 and the assumption of constant handling and market costs, each graphite racket provides about $38 more in profits.

SNOW SKIING EQUIPMENT

The Applications

In recent years graphite fiber has found its way into several snow skiing products including alpine and cross-country skis and poles. Graphite/epoxy has been particularly well accepted for use in ski pole shafts because it provides the poles with greater stiffness and durability than the more traditional materials, while still offering adequate shock absorbing properties. Traditionally, ski poles have been made with aluminum alloys, fiberglass and Tonkin bamboo. Today poles, both for downhill and cross-country skiing, are also available in graphite/aluminum and graphite/fiberglass combinations. Each type is available with various tips and grips to provide the skier with the desired use characteristics. Ski poles are very often extruded (except from natural materials) and may be wrapped with a complementing material to provide additional stiffness and, thus, increased stability.

The use of graphite in skis is a much more complicated issue. Its use is still rather limited by its stage of development and its high cost. In designing a ski many factors are considered. Materials are selected on the basis of a large number of sometimes conflicting criteria. These include:

- Strength
- Durability
- Effect on performance
- Material cost
- Effect on construction method
- Appearance
- Compatability with adhesive system used for bonding
- Effects of temperature in manufacture and in use. [14]

In order to be durable a ski must be able to withstand bending and twisting as well as temperature and humidity extremes. In general, materials, such as graphite, with high strength-to-weight ratios are used in the load carrying layer and the outer parts of the ski that undergo the greatest stress as the ski bends or twists.

There are two basic methods of modern ski construction. These are the torsion box method or wet wrap and the laminate or "sandwich" method. Generally each seeks to produce a ski with a reasonably flexible section at the tip or front of the ski, a stiff central section for stability and bite and usually a reasonably stiff rear section. A continuous distribution without stiffness irregularities between these sections is required. In addition to longitudinal stiffness, torsional rigidity and lateral stiffness are required.

The *laminate or sandwich* construction uses layers of either precured or prepreg material laminated to top and bottom of the central core layer. In the torsion box method, the core, which can be partially hollow, is wrapped with a continuous, wet layer of the structural material. In the United States Olin, Hexcel and Hart use the sandwich method, while Lange and Durafiber use the wet wrap process [15].

Table 11 presents some of the physical properties of materials used in the load-carrying layers of the ski. The same materials are used in both the torsion box and laminate methods of production. Note that the graphite/epoxies rank highest in terms of elastic modulus, tensile strength and shear modulus, and that only the aluminum alloy exceeds its shear strength. Generally the following materials are used in the core layer:

- Ash wood
- Okume wood
- Polyurethane foam
- Aluminum honeycomb
- Arimid honeycomb
- Fiberglass.

Steel is used for the bottom edge and Polyurethane, ABS and phenolic are used on the outer surfaces [15].

The Economic Incentives

As in each of the other sporting goods areas, the economic incentive to manufacture and sell graphite skiing equipment is determined by the equipment market as a whole, consumer preference for graphite products and the relative profitability of each of the graphite products.

In 1978 U.S. consumers spent $205.2 million on downhill and cross-country skis and poles [16]. Table 12 presents the distribution of this total among individual types of equipment. Tables 13 and 14 present the geographic distribution of ski and pole purchases and the distribution of purchases by family income level. Note that downhill equipment is more often purchased by individuals of families with $25,000 or greater annual incomes.

Ski equipment prices show a great deal of variation by construction materials. Tables 15 and 16 show some of the suggested retail price differences by construction of downhill skis and cross-country ski poles respectively.

As in tennis equipment, the cost comparison between a fiberglass pole and graphite pole is dependent on the material cost differences. A cross-country pole shaft may weigh about ten ounces if the total pole is to be a lightweight pole of 12 ounces (0.75 kilograms). Because the production process is simpler than in tennis rackets, a somewhat lower scrappage rate of about 10 percent is expected. Using the same method and process described in the tennis racket example, the graphite material would cost $20.31 and the fiberglass material would cost $5.50. Each graphite pole would then cost $14.80 more to produce.

As an example of the potential profitability of these graphite shaft poles (assuming a large enough volume in such sales to justify the fixed production costs),

TABLE 11 PHYSICAL PROPERTIES OF MATERIALS USED IN LOAD CARRYING LAYERS OF ALPINE SKIS

MATERIAL	ELASTIC MODULUS MSI	TENSILE STRENGTH KSI	SHEAR MODULUS MSI	SHEAR STRENGTH KSI	DENSITY LB/IN^3
ALUMINUM (7075-76)	10.5	78	3.8	32	0.098
UNIDIRECTIONAL REINFORCED EPOXY					
E-GLAS	4.9	175	0.5	10	0.075
S-GLAS	8.0	260	0.5	10	0.073
HIGH MODULUS GRAPHITE	32.0	175	0.7	10	0.058
HIGH STRENGTH GRAPHITE	20.0	220	0.65	14	0.057
KELVAR-49	12.5	220	0.3	6	0.050

SOURCE: "INFLUENCE OF COMPOSITE MATERIALS ON ALPINE SKI DESIGN," HERBERT C. BOEHM, SAMPE JOURNAL, SEPTEMBER/OCTOBER 1979, P. 17.

TABLE 12 U.S. CONSUMER PURCHASES OF SNOW SKIING EQUIPMENT IN 1978

TYPE OF EQUIPMENT	NUMBER OF PAIRS BOUGHT (1000)	AVERAGE PRICE ($)	TOTAL VALUE (1000$)
DOWNHILL SKIS	963	124.61	120,000
CROSS-COUNTRY SKIS	910	65.49	59,596
DOWNHILL POLES	961	15.99	15,366
CROSS-COUNTRY POLES	815	12.59	10,261

SOURCE: THE SPORTING GOODS MARKET IN 1979, PREPARED FOR THE NATIONAL SPORTING GOODS ASSOCIATION BY IRWIN BROH & ASSOCIATES, INC., DES PLAINES, ILLINOIS, 1979, P. 60.

TABLE 13 GEOGRAPHIC DISTRIBUTION OF SNOW SKIING EQUIPMENT IN 1978 (PERCENT)

GEOGRAPHIC REGION	DOWNHILL		CROSS-COUNTRY	
	SKIS	POLES	SKIS	POLES
NEW ENGLAND	13.3	11.4	8.6	8.0
MIDDLE ATLANTIC	20.2	21.0	24.9	18.5
EAST NORTH CENTRAL	20.5	15.9	41.6	42.3
WEST NORTH CENTRAL	6.4	6.4	8.6	8.2
SOUTH ATLANTIC	5.2	9.1	.5	-
EAST SOUTH CENTRAL	-	-	-	-
WEST SOUTH CENTRAL	.7	5.0	1.5	2.7
MOUNTAIN	7.8	6.9	8.8	8.9
PACIFIC	25.9	26.3	5.5	11.4
TOTAL	100.0	100.0	100.0	100.0

SOURCE: THE SPORTING GOODS MARKET IN 1979, PREPARED FOR THE NATIONAL SPORTING GOODS ASSOCIATION BY IRWIN BROH & ASSOCIATES, INC., DES PLAINES, ILLINOIS, 1979, PP. 64-67.

TABLE 14 ANNUAL FAMILY INCOME OF PURCHASER OF SNOW SKIING EQUIPMENT IN 1978 (PERCENT)

ANNUAL FAMILY INCOME	DOWNHILL		CROSS-COUNTRY	
	SKIS	POLES	SKIS	POLES
UNDER $10,000	8.9	9.9	9.9	4.0
$10,000 - $14,999	12.7	15.0	15.0	14.6
$15,000 - $19,999	17.5	16.9	22.1	26.2
$20,000 - $24,000	24.6	23.2	24.9	22.3
$25,000 AND OVER	36.3	35.0	28.1	32.9
TOTAL	100.0	100.0	100.0	100.0

SOURCE: THE SPORTING GOODS MARKET IN 1979, PREPARED FOR THE NATIONAL SPORTING GOODS ASSOCIATION BY IRWIN BROH & ASSOCIATE., INC., DES PLAINES, ILLINOIS, 1979, PP. 64-67.

TABLE 15 DOWNHILL SKI MODELS AVAILABLE FROM RETAINERS IN THE UNITED STATES, 1980

CLASS NUMBER	CONSTRUCTION	RANGE OF PRICES ($ PER PAIR)		NUMBER OF MODELS IN CLASS	PRICE OF AVERAGE MODEL ($ PER PAIR)
		LOW	HIGH		
1	FOAM/FG	60	295	86	188
2	WOOD	115	240	34	174
3	FG	175	250	14	217
4	AL/FG	129	268	12	218
5	AL/FG/FOAM	50	235	12	195
6	FG/FOAM/METAL (AL)	125	300	12	212
7	FOAM/METAL (AL)	130	210	6	169
8	FG/METAL	180	265	4	226
9	FG/WOOD/METAL (AL)	240	295	3	258
10	METAL	230	235	2	233
11	FOAM/CF	-	-	1*	265
12	WOOD/CF	-	-	1*	275
13	FG/ARAMID	-	-	1	275
14	CF/KEVLAR	300	300	2*	300
15	OTHER	150	255	5	207

AL-ALUMINUM
CF-CARBON FIBER
FG-FIBERGLASS

*THE AVERAGE PRICE OF SKIS USING GRAPHITE COMBINED WITH OTHER MATERIAL(S) IS $285.

SOURCE: SKIERS 1980 DIRECTORY, SKI-EARTH PUBLICATIONS, INC., BOSTON, 1979, PP. 40-69.

TABLE 16 CROSS-COUNTRY SKI POLE MODELS AVAILABLE FROM RETAILERS IN THE UNITED STATES, 1980*

CLASS NUMBER	CONSTRUCTION	RANGE OF PRICES ($ PER PAIR)		NUMBER OF MODELS IN CLASS	PRICE OF AVERAGE MODEL ($ PER PAIR)
		LOW	HIGH		
1	CF/AL	-	-	1	100
2	CF/FG	30	70	6	52
3	AL	14	43	14	26
4	FG	12	38	21	17
5	T	7	13	10	10
6	CF	70	100	6	84

CF-CARBON FIBER
AL-ALUMINUM
FG-FIBERGLASS
T-TONKIN BAMBOO

*DOES NOT INCLUDE LILJEDAHL BRAND MODELS.

SOURCE: SKIERS 1980 DIRECTORY, SKI-EARTH PUBLICATIONS, INC., BOSTON, 1979, PP. 40-69.

consider one U.S. company that sells both a graphite/epoxy and a fiberglass/epoxy cross-country ski pole. Both are suggested for experts to racers and in competition. Both types have similar adjustable straps and Delta wing baskets. The graphite pole is, however, offered in smaller size increments. The fiberglass pole sells for $29 per pair and the graphite sells for $70 per pair. Thus the graphite pole provides potentially $26 more profit per pair to the manufacturers, distributers and retailers of the product.

OTHER SPORTING GOODS

Fishing Equipment

Another area where graphite is rapidly gaining popularity is in fishing rods. Several leading manufacturers have introduced rods of graphite/epoxy, graphite/fiberglass/epoxy and boron/epoxy. Those on the market today range from the very lightweight fly rods to the much heavier rods used for deep sea fishing. The advantage of using the lightweight composite material is somewhat dependent on the style of the rod. Each of the rods is much lighter in weight than its fiberglass or bamboo counterpart, and this is an advantage in all cases because it means increased responsiveness or a better "feel." The graphite epoxy also increases the vibration damping ability of the rod. This is a particular advantage in a fly rod because the reduced vibration lowers the drag on the line immediately after the cast, resulting in casts of greater distance. Fly fishermen generally indicate distance increases of over 20 percent [17].

The fishing rod business is quite large. In 1978 U.S. consumers bought 4.3 million separate rods and six million additional rods in combination with reels. Total expenditures for these amounted to over $200 million [18]. The fishing rod business does, however, present an additional set of challenges to the manufacturers of graphite rods in that a large percentage of the rods purchased are purchased by individuals in families with relatively low annual incomes. Therefore, for a large portion of the potential market, the relative prices of various rods may be an important issue in rod selection. Table 17 shows the distribution of 1978 consumer purchases of fishing rods by annual family income.

An additional economic factor that must be considered by graphite rod producers is the geographic distribution of industry purchases. Table 18 shows this geographic distribution. Purchases are spread more evenly over the entire country than are purchases of most other sporting equipment types. This may further increase the costs of rods at the retail level by increasing transportation needs and costs.

In spite of these market related difficulties and their high price, the demand for graphite rods seems to be growing rapidly. Some sources predict that the demand for graphite rods may increase by as much as 20 percent per year to account for perhaps 25 percent of the wholesale value of all fishing rods by 1983 [19]. Several major manufacturers have introduced a large number of models using graphite. For example Graftek, a division of Exxon Enterprises, recently introduced 60 new "Precision Fishing Instruments." Of these, 22 are graphite. An additional 28 are a combination of graphite and E-Glass and only 10 are made of fiberglass alone [20].

In addition to Graftek/Exxon, the following companies are among the leading manufacturers of graphite fishing poles:

- Carbonite/3M
- Fenwick Products
- J. Kennedy Fisher, Inc.
- Lake King Rod Co.
- Lamiglas, Inc.
- Research Engineering
- Shakespeare/Columbia
- Skyline Industries. [21]

Bicycle Frames

The bicycle industry grew rapidly during the 1970s. The reduction in weight provided by the use of graphite components is an advantage to both the bicycle racer and the recreational rider. Table 19 provides a component weight comparison for a conventional 10-speed racing bike and a racing bike with graphite components. Note that the conventional bike used in this comparison is a high performance bike that would retail in the $500 to $600 range (1975 dollars). In this type of bicycle a 3.6 lb. (1.8 kg) weight savings or a savings of 14.9 percent is realized.

Other Sporting Equipment

In addition to those applications discussed above, graphite is being used in a wide variety of sporting goods. In each case its very high strength-to-weight and stiffness-to-weight ratios in combination with its shock absorbing characteristics and other physical properties of importance in use and production make it an advantageous material. It is being used to replace the more traditional materials of steel, aluminum, fiberglass and wood.

Some of the other sporting equipment applications of graphite fiber or graphite/epoxy include:

TABLE 17 DISTRIBUTION OF U.S. CONSUMER PURCHASES OF FISHING RODS AND ROD-REEL COMBINATIONS IN 1978 BY ANNUAL FAMILY INCOME (PERCENT)

ANNUAL FAMILY INCOME	ROD	ROD-REEL COMBINATIONS
UNDER $10,000	20.4	25.9
$10,000 - $14,999	21.4	21.9
$15,000 - $19,999	24.0	22.5
$20,000 - $24,999	14.5	13.7
$25,000 AND OVER	19.7	16.0
TOTAL	100.0	100.0

SOURCE: THE SPORTING GOODS MARKET IN 1979, PREPARED FOR THE NATIONAL SPORTING GOODS ASSOCIATION BY IRWING BROH & ASSOCIATES, INC., DES PLAINES, ILLINOIS, 1979, PP. 40-41.

TABLE 18 GEOGRAPHIC DISTRIBUTION OF U.S. CONSUMER PURCHASES OF FISHING RODS AND ROD-REEL COMBINATIONS IN 1978 (PERCENT)

GEOGRAPHIC REGION	RODS	ROD-REEL COMBINATIONS
NEW ENGLAND	2.1	2.5
MIDDLE ATLANTIC	11.5	11.9
EAST NORTH CENTRAL	20.5	20.7
WEST NORTH CENTRAL	7.5	8.8
SOUTH ATLANTIC	15.1	20.9
EAST SOUTH CENTRAL	2.9	5.8
WEST SOUTH CENTRAL	11.2	13.8
MOUNTAIN	9.7	4.4
PACIFIC	19.5	11.2
TOTAL	100.0	100.0

SOURCE: THE SPORTING GOODS MARKET IN 1979, PREPARED FOR THE NATIONAL SPORTING GOODS ASSOCIATION BY IRWIN BROH & ASSOCIATES, INC., DES PLAINES, ILLINOIS, 1979, PP. 40-41.

TABLE 19 COMPONENT WEIGHT COMPARISON FOR RACING BICYCLES

COMPONENT	CONVENTIONAL WEIGHT*		GRAPHITE WEIGHT	
	LBS	KG	LBS	KG
FRAME	4.7	2.1	3.1	1.4
FORK	1.8	0.8	1.1	0.5
RIMS	1.9	0.9	1.4	0.6
SPOKES	1.9	0.9	1.4	0.6
SEAT POST	0.8	0.4	0.5	0.2
SUBTOTAL	11.1	5.1	7.5	3.3
REMAINING COMPONENTS	13.0	5.9	13.0	5.9
TOTAL	24.1	11.0	20.5	9.2

*CONVENTIONAL 10-SPEED RACING BIKE OF THE HIGH-PERFORMANCE CATEGORY, RETAILING IN THE $500 TO $600 RANGE.

SOURCE: "OVERVIEW OF COMMERCIAL APPLICATIONS FOR GRAPHITE COMPOSITES," JON B. DEVAULT, HERCULES, INC., NATIONAL SAMPE SYMPOSIUM, 1975.

- Golf club head inserts
- Racquetball rackets
- Arrows
- Bows
- Water skis
- Ski boots
- Hockey sticks
- Javelins
- Cricket bat handles
- Parallel bars
- Kayaks
- Canoes
- Paddles
- Sail boat rudders, tillers, spars, etc.

Of these, archery equipment and boating supplies have had perhaps the widest distribution. It is expected that these and other sporting goods applications will begin to grow more rapidly, particularly as the price of graphite falls.

MISCELLANEOUS APPLICATIONS

Musical Instruments and High Fidelity Equipment

Violins and guitars have been designed and built with graphite-epoxy composite soundboards because aged spruce, the traditional construction material, is becoming more difficult to obtain. Laminated graphite-epoxy soundboards have been found to be more reproducible than those made of spruce and to stay better tuned because they do not absorb as much moisture or swell as much as wood. Graphite-epoxy instruments have also been found to give purer tones than wood ones because the damping coefficient of graphite-epoxy exceeds that of spruce at high frequencies. One such instrument is Ovation's "Glen Campbell" guitar which sells for $2,500 [22].

The acoustic properties of graphite reinforced plastics are also used to advantage in the pickup arm of the Sony phonograph. The good damping characteristics and high modulus of the arm minimizes distortions which otherwise would reach the transducer. The light weight of the arm makes lateral tracking much more precise while minimizing wear of the record grooves [23].

Graphite fibers are also being used to make shallow loudspeakers of high quality. The speed of sound on the surface of a molded graphite fiber speaker cone is about three times that on the surface of a regular speaker. This results in a more shallow cone which can be placed in inconspicuous cases or which can be fitted in normally inaccessible places such as automobile doors. Such speakers have been made in Japan and are marketed in the United States by Poly Audio, Inc. of Baltimore, Maryland.

Medical Applications

A number of interesting medical applications of advanced composites have been investigated and developed such as radiological equipment and external and implantable prosthetic devices.

The recognition that dangerous side effects can occur to human beings when subjected to excessive radiation doses requires that medical equipment limit the amount of patient exposure to x rays. Any type of material between the patient and the film recording the x ray will absorb some portion of the x rays and increase the dosage level that must be applied to the patient to get a clear x ray view. Structures between the patient and film include film cassette holders and patient support devices. In order to have sharp, focused radiographs, these components are required to be stiff and exhibit minimal deflection under the patient load, yet must also be as thin as possible to minimize x ray absorption. Graphite-epoxy composites are fairly transparent to x rays because of the low atomic number of carbon. This property, combined with their high structural integrity and stiffness, makes graphite composites an excellent choice as a structural material. Angiographic compression plates are currently being manufactured with graphite fiber composites as are body support structures such as therapeutic x ray table tops and tomography body scanner patient support couches [24].

Radiographic table tops and related equipment are currently being made with graphite composites by a number of European firms such as Philips in the Netherlands and Siemens Corp. in West Germany. Medical x ray manufacturers in the United States that are becoming seriously interested in manufacturing this equipment include the U.S. affiliates of these firms as well as Picker Corp. of Cleveland, Ohio, General Electric Company, Medical Systems Division of Milwaukee, Wisconsin and Litton Medical Systems of Des Plaines, Illinois. According to industry sources, a market of 200-300 large table tops per year is seen for this equipment, and some additional units might be required if existing installations are to be modified.

The Veterans Administration is currently funding the Browning Manufacturing Co. to make prototype graphite-epoxy components for artificial legs. These include heels and ankle assembles. Preliminary results have been encouraging, but significant further effort is required to reach production stage. External prosthetic devices appear to be a natural application of advanced composites.

Carbon-carbon composites may be a useful material in a variety of transcutaneous applications. Pyrolitic graphite has been found to be biocompatible with the human organism; it is clinically accepted and is currently used in the construction of cardiovascular prosthesis devices [25]. The main drawbacks of pyrolitic graphites are its mediocre strength and brittleness. Carbon fiber reinforced carbon (CFRC) shows much improvement in these properties and being wholly made of carbon remains biocompatible. Medical applications have been explored in Cardiff, Wales and in Brazil in close association with various hospitals in San Paulo. Two clinically successful applications have been CFRC pins for bone adjustment and heart valves [26]. Potential applications of CFRC that have been proposed include the fixation of artificial limb extensions to the stump of amputated limbs, total joint replacement, especially hip arthoplasty, and dental implants (artifical tooth roots), among others.

More mundane medical applications of advanced composites being considered include lightweight mechanical supports and equipment for orthopedic and handicapped patients. These include wheelchairs and braces. Other potential uses of advanced composites include crutches or casting formulations. It is current orthopedic practice to use fiberglass casts instead of the traditional, much heavier Plaster of Paris casts. Plaster of Paris casts are still used where a high degree of rigidity is desired, for example in a mobile leg cast of a heavy patient. Graphite composite could be used to make a truly mobile lightweight cast of required rigidity.

The Economic Incentives

Musical instruments and high fidelity equipment are typical consumer goods. In these applications, as in sporting goods, the economic incentive lies in the obtainable selling price of the product containing graphite. If the consumer believes that the final product is superior to the same item produced with a more traditional material, or if a more traditional material is expensive or difficult to obtain, there will be an economic incentive to produce the graphite-using good. If this incentive outweighs any incremental production costs associated with the graphite usage, the industry will choose to produce the graphite application.

In the area of medical applications economic incentives are more complicated. The relative costs of producing the devices with alternative materials are considered as described above. However, in some of the medical applications the use of graphite makes possible medical diagnosis and treatment that are not possible with the traditional materials. X ray tables allow clearer radiographs with reduced patient exposure. Prosthetic devices, bone adjustment pins and heart valves allow treatment of patients with reduced rejection by the body and reduced risk of infection. Because of this increase in biocompatibility it is possible that treatments may be more successful. In extreme cases the use of graphite composites may even save the patient's life. Thus the incentive to use graphite must be measured by evaluating the reduction in the costs associated with each incident of illness resulting from improved diagnosis and treatment. This includes not only cost differences directly associated with the graphite device but also cost differences associated with other treatments involved in the case. For instance, if an infection does not occur with the use of a graphite device that would have occurred with a traditional device, the overall treatment cost is reduced by the amount that would have been necessary to treat the infection. If a patient's life is saved, the value of that life must be included in the incentive for using graphite. Because these types of considerations are disease-specific, the economic incentives for devices in the medical area will be highly dependent on the individual use, and calculations of the general incentives are difficult.

SECTION 4

INDUSTRIAL GOOD APPLICATIONS

APPLICATIONS IN THE AEROSPACE INDUSTRY

The aerospace industry provides a testing ground for the development and deployment of carbon fiber containing composites. The demand for performance and safety has led to the use of carbon fiber in most aircraft. Military and civilian aircraft are using more carbon fiber, and the trends for the future imply greater use of composites. The thermal and physical properties of carbon fiber composites will lead to the widespread use of carbon fiber in helicopters, spacecraft, missiles, military aircraft and civil transport aircraft.

The U.S. government was responsible for providing the impetus for the development of the necessary technology for carbon fiber use. Carbon fiber composites were first used in noncritical, secondary structures such as hatch covers, doors, speed brakes and wing fairings. As knowledge of carbon fiber and its applications improved, military aircraft began to utilize the composites in primary structures such as wing fairings and spars. The F-16 and F-18 are good examples of carbon fiber composite use. The F-16 is the first design-from-the-start application for carbon fiber composites. Without the weight advantage of the composites, the F-18 could not achieve an acceptable performance. The AV-8B vertical takeoff fighter is also designed to incorporate the properties of carbon fiber composites. Previously, the military used carbon fiber composites to replace other composites used instead of designing the aircraft for carbon fiber use. The aircraft designed to use carbon fiber represent the commitment of the military to the use of millions of pounds of carbon fiber in American weapons.

Carbon fiber composites are being used in space vehicles and space structures. For space vehicle applications, the thermal and physical properties of carbon fiber make it very attractive. The cargo bay doors and experiment support pallets within the cargo bay doors of the Space Shuttle are constructed from carbon fiber composites. The weight advantage afforded by the use of carbon fiber gives the orbiter a usable payload capacity.

Carbon fiber structural elements are also used in space-borne antennae. Space antennae require dimensional control of surface imperfections to the order of a tenth of a wavelength. Such considerations lead to tolerance requirements of one centimeter over a surface of up to ten meters in diameter. Carbon fiber composites can be manufactured to meet these requirements for accuracy.

The NASA Langely Research Center, through the Large Space System Technology Program, is responsible for coordinating research and development efforts in support of future missions which will require large structures in space. These missions would use the Space Shuttle to ferry the building materials into space. The structure would be assembled from smaller sections in space using the Space Shuttle as a lifeline. NASA has identified 42 missions involving construction of structures in space. One proposed mission would be to construct a large collector for converting solar energy to radio waves. The radio waves would be beamed to earth and would be converted to electrical energy. If funding for these programs is continued, the volume of space and missile utilization of carbon fiber composites could equal the usage in aircraft.

Missiles are being constructed with varying amounts of carbon fiber. The first commitment to composites as primary structures on a strategic missile was Trident 2. Weight savings are most cost-effective in the launch vehicle's upper stages. Therefore, graphite-epoxy was considered for the third stage. Development programs focusing on the MX missile have produced studies of the use of composites in upper stages. These studies are being continued, and composites seem likely to have significant use on the MX missile body structure. The MX missile will also use carbon fiber in the missile canister. Over seven million pounds of carbon fiber will be used in 230 missile canisters. More extensive use of carbon fiber in missile systems is proposed. With the changing demands on cruise and supersonic missiles, the payoff for introducing composites is expected to increase.

The Army's Advanced Composite Airframe Program is funding the development of an all-composite helicopter fuselage. The objective of this program is to produce and evaluate an airframe that will achieve a 22 percent weight savings and 17 percent cost savings over conventional metal airframes. Other programs have led to the development of carbon fiber tail rotors and tail rotor drive shafts.

Applications of carbon fiber in civil transport aircraft are being studied by NASA's Aircraft Energy Efficiency Project. Development of secondary structure elements for flight evaluation such as spoilers, elevators, rudders and ailerons are being pursued. The effort also involves primary structures such as horizontal stabilizers and vertical stabilizers. The increasing cost of fuel has prompted the manufacturers of transport aircraft to use more carbon fiber. Boeing's 767 is the first commercial transport to incorporate carbon fiber composites as part of the original design. Smaller business aircraft manufacturers are now beginning to use carbon fiber in their designs too. The problems and delays associated with obtaining an FAA certification appears as the principal limitation for application to new designs for business aircraft.

Table 20 describes the applications and amounts of carbon fiber composites in aircraft. Many civilian aircraft are test models using small amounts of carbon fiber. Slightly different configurations of carbon fiber are used in different programs. Newer civilian transport aircraft are incorporating carbon fiber in their design instead of simply adding carbon fiber on existing aircraft. As the programs develop, more civilian transport aircraft will use carbon fiber. The military aircraft programs are more extensive. Carbon fiber is being used in production aircraft as well as test planes. The trend depicted shows greater use of carbon fiber in newer aircraft. New military aircraft use substantial amounts of carbon fiber. Carbon fiber can increase the performance and efficiency of aircraft, but significant cost-benefit analysis needs to be conducted to determine the future use of carbon fiber in civilian aircraft.

TABLE 20 USE OF CARBON FIBER IN AIRCRAFT

AIRCRAFT TYPE	NUMBER OF AIRCRAFT	COMPONENTS	POUNDS OF CARBON FIBER
MILITARY AIRCRAFT			
F-4 PHANTOM	4	ACCESS DOORS	5 PER AIRCRAFT
MCDONNELL-DOUGLAS S-3 VIKING	10	LOWER SPOILERS	8.6 PER ITEM
VOUGHT A-7 CORSAIR	7	WING PANEL	50 PER ITEM
VOUGHT F-111	200	WING FAIRINGS	20 PER ITEM
GENERAL DYNAMICS F-15 EAGLE	200	SPEED BRAKES EMPENNAGE ELEMENTS	∿ 160 PER AIRCRAFT
MCDONNELL-DOUGLAS F-16	ALL	EMPENNAGE	∿ 160 PER AIRCRAFT
GENERAL DYNAMICS F-18 HORNET	ALL	WING PANNELS, FLAPS, EMPENNAGE, DOORS	> 1,000 PER AIRCRAFT
MCDONNELL-DOUGLAS AV-8B HARRIER	ALL	WING, FORWARD FUSELAGE	> 1,000 PER AIRCRAFT
CIVIL AIRCRAFT			
BOEING 737	27	SPOILERS	52 PER AIRCRAFT
MCDONNELL-DOUGLAS DC-10	8	UPPER AFT RUDDER	∿ 30 PER ITEM
BOEING 727	10	ELEVATORS	∿ 65 PER AIRCRAFT
MCDONNELL-DOUGLAS DC-10	10	UPPER AFT RUDDER	∿ 30 PER AIRCRAFT
LOCKHEED L-1011	10	AILERONS	∿ 80 PER AIRCRAFT
BOEING 737	1	HORIZONTAL STABILIZERS	∿ 100 PER AIRCRAFT
MCDONNELL-DOUGLAS DC-10	2	VERTICAL STABILIZERS	∿ 330 PER AIRCRAFT
LOCKHEED L-1011	1	VERTICAL FIN	∿ 350 PER AIRCRAFT
BOEING 747	42	FLOOR PANELS	∿ 200 PER AIRCRAFT
BOEING 767	ALL	CONTROL SURFACES, ENGINE COWLS, FAIRINGS, LANDING GEAR, DOORS	∿ 2,000 PER AIRCRAFT
CESSNA CITATION III	ALL	FLAPS, FAIRINGS, ENGINE COWLS, LANDING GEAR, DOORS	∿ 150 PER AIRCRAFT
LEAR FAN LEAR AVIA	ALL	FUSELAGE STRUCTURE, WING STRUCTURE, EMPENNAGE, CONTROL SURFACES, PROPELLER	> 500 PER AIRCRAFT
OTHER AIRCRAFT			
BOEING HELICOPTERS			
CH-46	4	MAIN ROTOR BLADES	∿ 70 PER AIRCRAFT
CH-47	1		
SIKORSKY S-63 LAMPS UTTAS	ALL	TAIL ROTOR, FUSELAGE PANELS	∿ 50 PER AIRCRAFT
SIKORSKY S-73	ALL	TAIL ROTOR, DOOR PANELS	∿ 50 PER AIRCRAFT
SPACE SHUTTLE ORBITER	ALL	PROPULSION PODS, NOSE CAP, CARGO PALLETS, WING LEADING EDGE, SUPPORT STRUCTURE, CARGO BAY DOORS	∿ 5,000 PER VEHICLE

A program funded by Boeing/NASA-Ames on the economic assessment of graphite fibers for aircraft interior applications is being evaluated by ECON. The program proposes the development of graphite fiber composites to replace fiberglass in advanced design commercial aircraft interior panels, partitions, ceilings and stowage bins. Based upon the weight savings estimates provided by Boeing Commercial Airplane Company, ECON demonstrated an approach to the economic evaluation of carbon fiber substitution.

The preliminary cost-benefit analysis compares the potential savings to the potential costs. The benefits of carbon fiber composites are due to their physical and thermal properties. Improved performance characteristics are load carrying capability, fracture toughness, flame ignition resistance and reduction in weight. Weight and performance can be translated into manufacturing and operational costs and benefits. The potential costs of carbon fiber substitution are increased material costs and research, development and deployment.

The two aircraft being considered are the 767 and the 747. Data was gathered to estimate fuel savings over entire fleets for a 15-year operation life. The estimated fuel savings for the fleet of 747s is between $36 and $54 million over a 15-year operational life. The estimated cost of carbon fiber substitution for the fleet of 747s was $7.7 million. The findings for the 767 were similar. The change in cost for graphite in the finished part represents 14 to 21 percent of the total savings over the life of a 747 aircraft. For a 767 aircraft, the substitutions represent 26 to 38 percent of the total savings over the life of a 767 aircraft.

The methodology used to determine the costs and benefits for carbon fiber substitution in civilian transport aircraft was fairly straightforward and based on constant 1980 dollars. Two plane types were considered: the four-engine 747 and the three-engine 767. Boeing provided the data to determine the weight and fuel savings per aircraft due to carbon fiber substitution. The estimates of fuel savings were determined by an average trip for the plane type. Tables 21 and 22 describe the weight and fuel savings for carbon fiber substitution respectively. The areas of substitution and the weight savings over fiberglass are specified for the 767 and 747. The average trip for a 747 is assumed to be 2,000 miles and 1,000 miles for the three-engine 767. It was also assumed that a 747 travels 1.5 million miles per year and the 767 travels 1.2 million miles per year. The weight savings from carbon fiber correspond to a saving of nine gallons of fuel per trip for the 747 and 1.6 gallons for the 767 as shown in Figure 1. Multiplying the gallons saved per trip by the number of trips per year gives the total gallons saved each year per aircraft. For a 747 this equals 6.750 gallons per year and 1,920 gallons for a 767. The next step is to estimate the fuel savings for a fleet of aircraft. There will be 356 four-engine 747s and 1,383 three-engine 767s by 1990. This corresponds to an annual savings of 2.4 million gallons per year for the 747s and 2.7 million gallons per year for the 767s. To estimate the savings over the life of the airplane fleets, a conservative 15-year operational life was used. Over a 15-year operational life of each aircraft, 36 million gallons will be saved for the four-engine 747 fleet and 40 million gallons for the three-engine 767 fleet. Table 22 explains the calculations.

The final step in the cost-benefit analysis is to compare the expected costs to the potential savings. The cost of fuel is the major factor in estimating the savings for the aircraft. If the price of aviation fuel is $1.50 per gallon in 1990, the estimated savings for the lifetime of the fleet of 747s is $54 million and $60 million for the 767s. The cost of graphite materials substitution for a fleet of 747s is estimated to be $8 million dollars and $14 million for the fleet of 767s as explained in Figure 2. Given the preceding assumptions, the additional cost for graphite in the finished parts take from three to five years of operation to recover. This short payback period makes the substitution a viable economic alternative for increasing the fuel efficiency of civilian transport aircraft.

The aerospace applications for carbon fiber composites are extensive. Use of the composites is expected to increase, and the technology used in manufacturing and fabricating the composites is improving. The nature of the aerospace industry ensures the expanding use of carbon fiber in the future.

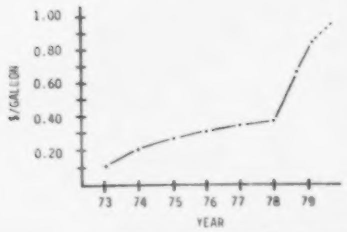
TABLE 21 ESTIMATED WEIGHT SAVINGS (BASED ON BOEING DATA PRESENTED 9/22/80)						
AIRCRAFT TYPE	AREA (FT^2)	NUMBER OF PLIES	TOTAL AREA (FT^2)	181 GLASS (LB)	GRAPHITE (LB)	WEIGHT SAVINGS (LB)
747 AIRCRAFT						
SIDEWALLS	1,109	1	1,109	67.0	42.4	24.6
PARTITIONS	225	2	450	27.2	17.2	10.0
STOWAGE BINS	5,185	2	10,370	626.4	396.1	230.3
CEILINGS	2,342	1	2,342	141.5	89.5	52.0
TOTAL			14,271	862.1	545.2	316.9
767 AIRCRAFT						
SIDEWALLS	731	1	731	44.2	27.9	16.3
PARTITIONS	62	2	124	7.5	4.7	2.8
CEILINGS	782	2	1,564	94.5	59.7	34.8
ACCOUSTICAL CEILINGS	112	1	112	6.8	4.3	2.5
STOWAGE BINS	1,210	2	2,430	146.2	92.4	53.8
	1,126	1	1,126	68.0	43.0	25.0
	175	2	350	21.1	13.4	7.7
TOTAL			6,427	388.3	245.4	142.9

NOTE: WEIGHT OF 181 GLASS = 8.7 OZ/YD^2 OR 0.0604 LB/FT^2
WEIGHT OF GRAPHITE = 5.5 OZ/YD^2 OR 0.0382 LB/FT^2

TABLE 22 FUEL SAVINGS				
AIRCRAFT TYPE	NUMBER OF TRIPS PER YEAR	OPERATIONAL LIFE (YRS)	FLEET SIZE	TOTAL TRIPS PER FLEET
747	750	15	356	4,005,000
767	1,200	15	1,383	24,894,000
AIRCRAFT TYPE	TOTAL TRIPS PER FLEET	GALLONS SAVED PER TRIP	COST PER GALLON	TOTAL DOLLARS SAVED
747	4,005,000	9	$ 1.50	$54,000,000
767	24,894,000	1.6	$ 1.50	$60,000,000

AIRCRAFT	EMPTY WT SAVED-LBS	PERCENT FUEL CONSUMPTION REDUCTION BASED ON SPECIFIC TRIP DISTANCE	LBS OF FUEL SAVED PER TRIP	EQUIV. GALLONS SAVED/TRIP
747	317	1% PER 5000 LBS WEIGHT = 970 FUEL LBS FOR 2000 MI TRIP	61.5	9
767	143	1% PER 1000 LBS WEIGHT = 75 FUEL LBS FOR 1000 MI TRIP	10.7	1.6

RANGE OF PROJECTED FUEL COSTS



SOURCE: AIR TRANSPORT ASSOC. REPORT, JAN. 1980

FIGURE 1 METHOD FOR DETERMINING FUEL SAVINGS

COST FOR 181 GLASS = \$1.40/LINEAR YD (38 IN. WIDE) OR \$.1474/FT^2

COST FOR GRAPHITE = \$45./LB OR \$1.7187/FT^2

747-200 AIRCRAFT	767 AIRCRAFT
14,271 FT^2	6,427 FT^2
181 GLASS - \$2,104. GRAPHITE - \$24,528. Δ = \$22,424.	181 GLASS - \$947. GRAPHITE - \$11,046. Δ = \$10,099.

MATERIAL COST OF SUBSTITUTION PER FLEET

FOR 356 747S--356 X \$22,424. = \$14 MILLION

FOR 1,383 767S--1,383 X \$10,099. = \$8 MILLION

FIGURE 2 MATERIAL COSTS PER AIRCRAFT

AUTOMOTIVE APPLICATIONS

Introduction

The drive towards improved fuel economy has accelerated efforts to reduce vehicle weight. In addition to designing and producing small cars, manufacturers are actively pursuing the substitution of lightweight materials for conventional ferrous metals. The potential market for these materials will depend upon their economic feasibility as well as their material properties. Though the design benefits of graphite reinforced composite materials are clear, e.g., equal or superior stiffness and greatly reduced weight, the material is currently not economically feasible. The key issues to consider when analyzing the potential market for graphite composites are: 1) the future price of graphite fiber; 2) the economics of high volume manufacturing; 3) the price and availability of competing lightweight materials; 4) the costs of alternative fuel saving technologies such as diesel engines and 5) future fuel economy standards. In the following paragraphs the technical advantages offered by GRP will be reviewed. The economic incentives behind GRP will then be studied, and several specific structural applications will be discussed.

Technical Advantages

Research interest in automotive applications of advanced composite materials started in the early 1970s. The interest intensified with the increases in the price of petroleum fuel and energy legislation. Currently all the major automotive manufacturers have active development programs investigating the potential use of advanced composites to automotive structures, and a wide variety of prototype automotive components have been made out of resin matrix composites. Reinforcing materials used have included graphite and aramid, alone or mixed with fibrous glass. Approaches have included the reinforcement of metal with organic composites, but little has been done with metal matrix composites.

In a well publicized program the Ford Motor Company built and recently exhibited at the 1979 SAE Exposition in Detroit, Michigan, an experimental automobile that uses advanced composite materials, mainly graphite composites, to as great an extent as possible, while retaining the appearance and performance characteristics of the Ford Granada, an intermediate size automobile. Depending on the specifics of a particular component, a composite part may weigh from about 20 percent to 60 percent of the weight of the steel part it replaces. Use of these composite components in a vehicle will result in a significant reduction in vehicle weight and a corresponding improvement in fuel economy. For example, the Ford Light Weight Vehicle has a curb weight of 2517 lb. (1143 kg), or 1230 lb. (657 kg) less than that of the standard Granada. Because of lower structure weight, a smaller engine, a 2.8 liter V-6 instead of a 5.8 liter V-8, can be used without changing performance (0-60 mph, (100 km/hr) in 12 sec.). Fuel economy (metro/highway) increases from 17 mpg for the standard Granada to 23 mpg for the LWV. In summary, substituting graphite composites for steel in this automobile results in a 31 percent reduction in inertia weight and a 35 percent increase in fuel economy.

The current status of automotive uses of advanced composites can be summarized as follows:

- Parts that are the equivalent of steel parts in performance but significantly lower in weight have been built on an experimental basis with aerospace fabrication technology.
- These parts have passed a variety of laboratory tests successfully and have been found to perform well in actual service.
- The parts paint well and can be made to have a Class A finish.
- It is possible to reconfigure existing structures because one can design the desired degree of stiffness into a component.
- It is possible to integrate composite structures into a standard automotive system, as demonstrated by the Ford Light Weight Vehicle.
- There are no advanced components in full production use at the present time.

The Manufacturers Viewpoint--Case Study Assumptions and Methodology

Recently a case study was performed to estimate the necessary weights and costs for several different conventional and lightweight materials that could be used in a wide variety of structural applications. The result of this case study shed light on the competitiveness of carbon fiber composite vis-a-vis other lightweight materials. In general the results show that other less expensive, alternative lightweight materials are more attractive to manufacturers at present.

In practice the list of components and materials will vary with the nature of the problem at hand. For example, the component list could consist of all parts in a single subassembly, all parts of a particular geometry (i.e. solid section members), or all parts in the entire automobile. The list of competing materials could include ferrous metals, reinforced plastics or some combination of both. Three principles were followed in the selection of candidate components:

1. Each component should possess a significant potential for absolute weight reduction by virtue of its large present weight. Consequently, the minimum component weight considered was six pounds. In some cases, components which were subassemblies, such as hoods, were considered as single units.
2. Each component must serve a significant load-bearing function, so that its design is governed by stiffness and/or strength considerations. All such components considered were generally fabricated from mild steel.
3. No component should be required to withstand high temperature exposure, thereby excluding all engine components.

The components selected for study were taken from the detailed breakdown of vehicle components for a 1975 Chevrolet Chevelle two-door sedan. The Chevelle analyzed was a model IAC37 Malibu Colonnade HTR Coupe equipped with a 250-IBBI I-6 engine, a three-speed transmission with essentially no optional equipment. Though this vehicle precedes downsizing and front wheel drive, publicly available weight and cost data for the Chevelle were more complete than for recent models [27]. Twenty-six components are listed in Table 23 which meet the three criteria above. The FS and RS refer to front and rear suspension. Forty-nine percent of the vehicle curb weight of 3,643 pounds is represented by this list.

As shown in Table 24, nine alternative materials mixes were chosen as competitors for each component application. For simplicity, all mixes are referred to by the principal material of construction. A steel front fender assembly, for example, could contain zinc. The plastic mixes use either unsaturated polyester (for thermosets) or nylon 6-6 (for thermoplastics) matrices reinforced with the following fibers:

- E-glass
- High modulus graphite
- High modulus graphite/E-glass hybrids: 10/90,20/80,40/60
- High strength graphite.

For the hybrid composites, the characteristic numbers refer to the relative volume concentration of graphite fiber to glass fiber in the composite. In the analysis it is

TABLE 23 CASE STUDY COMPONENTS

1. UNDERBODY
2. WINDSHIELD
3. SIDE PANELS
4. DECK OPENING
5. ROOF
6. DECK LID
7. FRONT FENDER ASSEMBLY
8. HOOD ASSEMBLY
9. HOOD HINGE/LATCH
10. RADIATOR SUPPORTS
11. FRONT SEAT FRAME
12. FRAME ASSEMBLY
13. ENGINE REAR CROSS
14. ENGINE SUPPORTS
15. ANTI-SWAY BAR
16. COIL SPRINGS (FS)
17. COIL SPRINGS (RS)
18. ROAD WHEELS
19. FRONT BUMPER
20. REAR BUMPER
21. PROPULSION SHAFT
22. CONTROL ARMS (FS)
23. CONTROL ARMS (RS)
24. DOOR HINGES
25. DOOR RAILS
26. DOOR PANELS

TABLE 24 ALTERNATIVE MATERIALS MIXES

METAL

1. MILD STEEL (ST)
2. ALUMINUM (AL)
3. HIGH-STRENGTH LOW-ALLOY STEEL (HSLA)

PLASTICS

4. E-GLASS (EG)
5. HIGH-STRENGTH GRAPHITE (HSG)
6. HIGH MODULUS GRAPHITE (HMG)
7. 10/90 HYBRID (10/90)
8. 20/80 HYBRID (20/80)
9. 40/60 HYBRID (40/60)

assumed that the composites would always contain 60 percent by volume fiber and 40 percent volume resin.

Weight Reduction Analysis--

The weights for steel components were taken from publicly available data on the 1975 Chevelle. The weights for the remaining eight materials in each of the 26 components were estimated by employing a method developed by Chang and Justusson [28]. The ratio between the weights of a given lightweight material (the unknown) and mild steel can be calculated as a function of the ratio for material density, elastic moduli and yield strengths. The functional relationship depends on the applicable design criteria, where the limiting design criteria is determined by deciding which classification best describes the component. The classifications are broadly based on geometry, such as panel members, solid section members and thin walled beams. For example, the limiting design criteria for panel members using isotropic materials is oil canning when the elastic modulus for the new material is less than the elastic modulus for mild steel. If the elastic modulus for mild steel is greater, the limiting criteria is local buckling. Table 25 classifies the case study components by geometry, while Table 26 gives the "equivalent weight ratio" for equivalent structures (geometries) for the case study materials.

Some modification of the methodology was required for the reinforced composites because composite parts designed for maximum stress in a principal direction may fail to meet design criteria due to minor stresses as a result of the anisotropic behavior of the material. To accommodate the minor stresses, cross-plies of various orientations were included in the composite, resulting in a lower effective strength and modulus in the principal direction than the maximum obtained using unidirectional composites. This reduction in material properties was represented in the generalized model with effective values for parameters in the principal direction. Since the cross-ply orientation used will vary with component type, different values were used for different applications.

A second modification was required when hybrid materials were used. A significant advantage of hybrid composites is that high performance fibers may be

TABLE 25 CLASSIFICATION OF VEHICLE COMPONENTS BY GEOMETRY

SOLID-SECTION MEMBERS	PANEL MEMEBERS	THIN-WALL BEAM MEMBERS
DOOR HINGES	UNDERBODY	WINDSHIELD COWL AND DASH
HOOD HINGES AND LATCH	ROOF	QUARTER PANELS
RADIATOR SUPPORTS AND BRACKETS	DOOR PANELS AND REINFORECEMENTS	DECK OPENING
ENGINE REAR CROSS MEMBER	DECK LID ASSEMBLY	DOOR RAILS
ENGINE SUPPORTS	HOOD ASSEMBLY	IMPACT RAILS
FRONT AND REAR BUMPERS	FRONT SEAT FRAME	FRONT FENDER
COIL SPRINGS		FRAME
		SUSPENSION CONTROL ARMS
		PROPULSION SHAFT
		ANTI-SWAY BAR
		ROAD WHEELS

TABLE 26 VALUES FOR WEIGHT RATIOS OF EQUIVALENT STRUCTURES FOR VARIOUS MATERIAL SUBSTITUTIONS

	GEOMETRY		
MATERIAL	SOLID-SECTION	PANEL SECTION	THIN-WALLED BEAM
STEEL	1.00	1.00	1.00
HSLA	0.80	1.00	0.80
ALUMINUM	0.55	0.60	1.00
HM GRAPHITE COMPOSITE	0.20	0.30	0.40
HS GRAPHITE COMPOSITE	0.25	0.35	0.60
E-GLASS COMPOSITE	0.40	0.75	1.90
HYBRID COMPOSITE (HM GRAPHITE/ GLASS)			
10/90	0.35	0.60	1.50
20/80	0.30	0.50	1.20
40/60	0.25	0.40	0.90

used at key locations of high stress in the composite, resulting in far greater mechanical performance than if they are uniformly distributed in the component. The effective stiffness and strength are greater than that predicted by a simple law of mixtures, although the average density is location independent. Several recent papers present design results for hybrid composites, which were used to derive effective parameters for the component classes used in this study [29, 30].

Cost Analysis--

The cost analysis examined the changes in fabrication process and manufacturing costs that would occur when the historic materials of construction were replaced by alternate materials. As pointed out before, the costs of the steel components for the baseline case were determined from publicly available data. The cost structure assumed was that of a major automotive manufacturer, in that most of the component parts would be manufactured in-house, and that only standard or specialized items would be purchased. The cost structure includes the cost of component assembly. It was assumed that the use of alternative materials would not influence or cause changes in corporate costs or profits. Referring to Figure 3, only items above the dashed line were considered in the analysis. Because of the emphasis on materials in this analysis, the manufacturing costs were broken down into two major elements:

- Direct Materials Costs
- Fabrication Costs.

The direct materials costs were based on the applicable purchase price of the materials in a form suitable for the production operation contemplated; for example, sheet metal of specified thickness for a stamping operation. In some instances purchased materials would have to be modified or processed further in an intermediate manufacturing operation in order to arrive at a material form suited to the component fabrication process. As shown in Figure 3, the direct materials cost to the component production operation are taken as the sum of the cost of purchased materials (from an outside vendor) and any fabrication costs associated with the intermediate materials processing operations including scrappage generated at this stage. The intermediate materials were treated as though they were purchased at cost from an outside vendor. For example, in the case of fiber reinforced plastic components, it was assumed that a manufacturer would make the needed molding compounds from purchased fibers, resins and fillers in-house, but in a cost center separate from the component fabrication operation. Data sources for direct material costs included U.S. government statistics, trade publications and various publicly available technical papers [31, 32]. All materials costs were stated in 1977 dollars. The price of graphite fiber was treated parametrically.

Fabrication costs consist of all other costs associated with the transformation of the raw materials into a finished product. These are normally segregated into costs that vary with the volume of production (variable costs) and the costs that remain constant regardless of the volume of production (fixed costs). For the case study the production levels of the individual components were geared to a vehicle production volume of 350,000 units per year.

When steel was replaced by another metal, such as aluminum or HSLA, it was assumed that the basic fabrication technology would not change, and that staffing, tooling and equipment requirements would remain the same. It was assumed that any nonmetallic materials or special fasteners originally present in the steel component

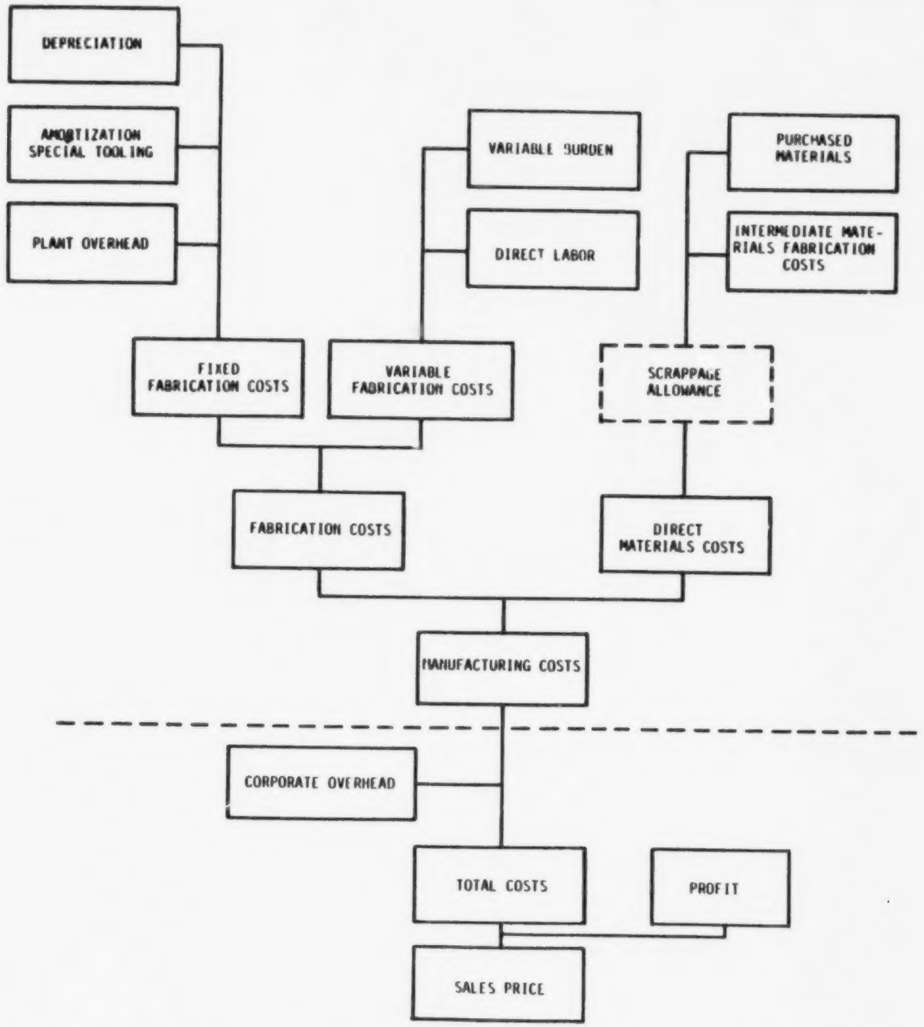


FIGURE 3 FLOW CHART SHOWING THE FORMULATION OF UNIT SALES PRICE FROM INPUT FACTORS

would also be present in the replacement part. Replacement of steel by another metal was assumed to result in changes in direct materials costs, but not in fabrication costs. These changes in direct materials costs would be due to differences in the relative weight and unit costs of the two metals.

The replacement of steel by the fiber reinforced composite would entail a basic change in fabrication technology and would require totally different equipment from that currently used to make a metal part. In order to estimate the manufacturing costs of various GRP components, it was necessary to:

1. Identify the manufacturing processes that could be used and choose a candidate process
2. Identify the product form of feed materials that would be required by the candidate process
3. Estimate the amount of feed materials required, and their costs based on the costs of raw materials and intermediate fabrication steps
4. Estimate the fabrication costs associated with transforming the feed materials into the desired components, taking into account the part-forming process, the subsequent secondary machining operations and parts assembly steps.

Both the selection of candidate fabrication processes and derivation of the associated capital costs were aided by several recent technical papers [33-44].

Case Study Results

The intent of the case study was to gain a better understanding of the usage rate of graphite fiber as a function of fiber price over a wide range of weight reduction goals. The economics of graphite reinforced composite were analyzed for two fiber prices, namely \$2/lb. (\$4.40/kg) and \$6/lb (\$13.20/kg). These prices were chosen for presentation here to illustrate; 1) the effects of an extremely low and unlikely price which would guarantee widespread use of graphite fiber in automobiles and 2) that the price of \$6/lb. (\$13.20/kg), low with the technology available today, implies that little graphite will be used. The results were generated by an algorithm which computes the minimum cost materials mix for a given weight constraint. Tables 27 through 29 illustrate the sensitivity of the optimal materials mix to fiber price and percent weight reduction for each component classified by structural geometry. The notation for each material is the same as used in Table 24. The percent weight reduction, which ranges from 10 to 45 percent, is that reduction possible for the entire automobile through 1) replacement of the historic mix by the indicated optimal mix and 2) savings from weight reduction. The analysis of weight reduction was based on a model presented by Adams, et al. [45]. This model suggests that weight propagation precedes unidirectionally from the upper body through the lower body and chassis, and finally to the power plant. The upper body, being at the top of the chain, achieves weight reduction through material substitution only. Savings in all other groups result from both substitution and propagation. In the interests of tractability, only point estimates of average weight propagation factors were calculated. An exercise was performed where, for a given set of 26 optimal mixes, the total weight reduction (relative to the historical case) due to both substitution and propagation was calculated. This number divided by the weight savings due to direct material substitution without weight propagation yields an estimate of the average propagation factor. This value, of course, is precise only for the particular optimal mix chosen and

TABLE 27 THIN-WALL BEAM MEMBERS

COMPONENT	FIBER PRICES $/lb.	PERCENT WEIGHT REDUCTION 10	15	20	25	30	35	40	45
WINDSHIELD (2)	$6	ST				HMG			
	$2	ST			HMG				
SIDE PANELS (3)	$6	ST					HMG		
	$2	ST					HMG		
DECK OPENING (4)	$6	ST					HMG		
	$2	ST					HMG		
FRONT FENDER ASSEMBLY (7)	$6	ST			HMG				
	$2	ST		HMG					
FRAME ASSEMBLY (12)	$6	HSLA						HMG	
	$2	HSLA						HMG	
ANTI-SWAY BAR (15)	$6	HSLA						HMG	
	$2	HSLA						HMG	
ROAD WHEELS (18)	$6	HSLA	EG	10/90	20/80			40/60	HMG
	$2	HSLA				20/80		40/60	HMG
PROPULSION SHAFT (21)	$6	EG	10/90	20/80			40/60		HMG
	$2	10/90	20/80			40/60			HMG
CONTROL ARMS (FS) (22)	$6	HSLA						HMG	
	$2	HSLA						HMG	
CONTROL ARMS (RS) (23)	$6	HSLA						HMG	
	$2	HSLA						HMG	
DOOR RAILS (25)	$6	HSLA					HMG		
	$2	HSLA						HMG	

TABLE 28 PANEL MEMBERS

COMPONENT	FIBER PRICES $/lb.	PERCENT WEIGHT REDUCTION 10 20 30 40
UNDERBODY (1)	$6 $2	ST———EG-20/80———40/60———HMG— ST-------40/60-------HSG-HMG---
ROOF (5)	$6 $2	ST-HSLA———20/80-40/60———HMG— ST-----HSLA-------40/60-------HSG-HMG---
DECK LID (6)	$6 $2	ST———20/80——40/60———HMG— ST-------40/60-------HSG-------HMG----
HOOD ASSEMBLY (8)	$6 $2	ST———AL———20/80-40/60———HMG— ST-------40/60-------HSG-HMG----
FRONT SEAT FRAME (11)	$6 $2	ST—EG———20/80——40/60———HMG— ST---40/60-------HMG----
DOOR PANELS (26)	$6 $2	ST———AL—20/80——40/60———HMG— ST-------40/60-------HMG----

TABLE 29 SOLID SECTION MEMBERS

COMPONENT	FIBER PRICES $/lb.	10	15	20	25	30	35	40	45
HOOD HINGE/LATCH (9)	$6	HSLA-EG		20/80	40/60				HMG
	$2	HSLA-40/60							HMG
RADIATOR SUPPORTS (10)	$6	EG		20/80		40/60			HMG
	$2	20/80--40/60							HMG
ENGINE REAR CROSS (13)	$6	HSLA-EG		20/80		40/60			HMG
	$2	HSLA	40/60						HMG
ENGINE SUPPORTS (14)	$6	HSLA-EG		20/80	40/60				HMG
	$2	HSLA-40/60 20/80							HMG
COIL SPRINGS (FS) (16)	$6	EG		20/80			40/60		HMG
	$2	20/80						40/60	HMG
COIL SPRINGS (RS) (17)	$6	EG		20/80			40/60		HMG
	$2	20/80						40/60	HMG
FRONT BUMPER (19)	$6	EG		20/80	40/60				HMG
	$2	20/80-40/60							HMG
REAR BUMPER (20)	$6	EG		20/80	40/60				HMG
	$2	20/80--40/60							HMG
DOOR HINGES (24)	$6	HSLA-EG		20/80		40/60			HMG
	$2	HSLA	40/60						HMG

the propagation model parameters from Adams, et al. [45]. Since the case study component substitutions do occur throughout the vehicle (instead of only in the chassis, for example) this value was believed to be a usefully representative average which can be used for most cases that involve normal material substitution and weight propagation. Referring again to Tables 27 to 29, note that graphite hybrids are present at the 10% weight reduction level when the fiber price is $2/lb ($4.40/kg). Except for the propulsion shaft, all of the components for which graphite appears at minimum cost are solid-section members, and the mix is the 20/80 hybrid. In all components the material mix changes follow the same overall progression (ST or HSLA, AL or E-Glass, 10/90, 20/80, 40/60, HSG, HMG) in order of increasing cost, although many mixes are skipped over. In some cases the optimal materials mix changes rapidly as weight is reduced. For example, component 14, the engine supports, go from an HSLA to a 20/80 to a 40/60 mix as weight reduction changes by less than 1 percent.

Compared to the $6/pound ($13.20/kg) case, at $2/pound ($4.40/kg) hybrids generally enter the solution sooner with fewer intermediate mix changes. But after the 40/60 hybrid becomes optimal for a given component, the switch to HMG occurs at approximately the same level of weight reduction for both prices.

At $2/pound ($4.40/kg) the panel members are mild steel (ST) in the minimum cost solution, switch to the 40/60 hybrid at 20 to 25 percent weight reduction, and then to HMG at 40 to 45 percent weight reduction. The thin-wall beam members (with the exception of the road wheels and propulsion shaft) start as either ST or HSLA, and then go directly to HMG. For some components HMG enters sooner at $2 than at $6 (windshield, 26 percent versus 30 percent; front fender assembly, 20 percent versus 28 percent) and for others HMG enters later (rear control arms, 43 percent versus 41 percent; door rails, 43 percent versus 37 percent). Finally, the solid-section members generally are HSLA or 20/80 hybrid in the minimum cost solution ($2/pound), shift to the 40/60 hybrid between 12 percent and 18 percent weight reduction and to HMG at 43-44 percent. The only exceptions are the coil springs, which remain 20/80 until around 42 percent weight reduction when 40/60 becomes optimal. This component is the only one for which a hybrid other than 40/60 remains in the solutions over a wide range of weight reductions.

Figures 4 and 5 summarize the results for each material across all components for the $2 and $6 a pound ($4.40 and $13.20 a kilogram) fiber price. Each horizontal line in both figures is a sum of the usage in pounds of all the materials represented below the line. Usage of a particular material is determined by subtracting vertical distances at a given weight reduction level.

Referring to Figure 4 for example, a weight reduction of 20% implies that the optimal mix contains 350 pounds (159 kilograms) of steel, 140 pounds (64 kilograms) of aluminum, 316 pounds (144 kilograms) of HSLA, 210 pounds (96 kilograms) of E-glass materials (including fiber and resin), 10 pounds (4.5 kilograms) of graphite fiber and 170 pounds (77 kilograms) of miscellaneous materials.

It is interesting that for the $6 a pound ($13.20 a kilogram) case, both aluminum and E-glass leave the optimal solution at about the 24% weight reduction level. In the $2 a pound ($4.40 a kilogram) case, E-glass and aluminum never enter the optimal materials mix. Note that as might be expected, graphite fiber usage increases dramatically as the weight constraint increases until finally when the entire auto's

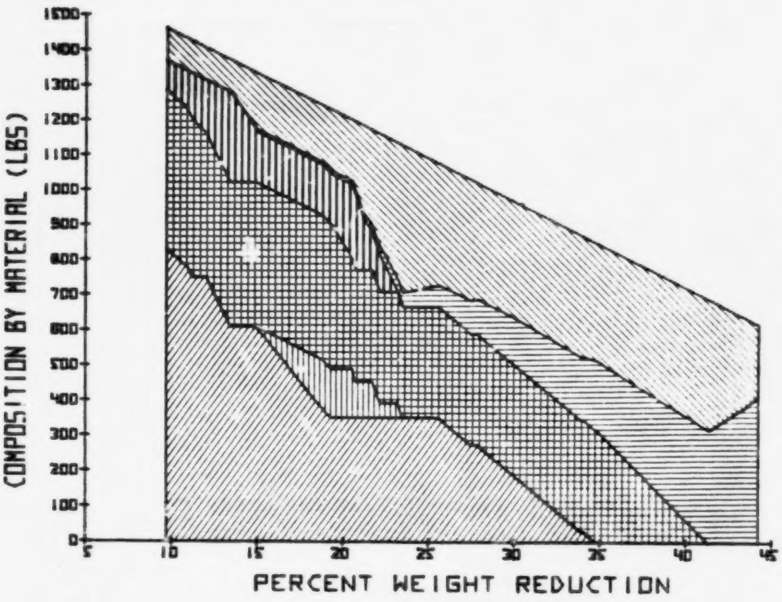


FIGURE 4 MATERIALS USAGE AND PERCENT WEIGHT REDUCTION (26 COMPONENTS, 9 MATERIAL MIXES, 1975 CHEVELLE)

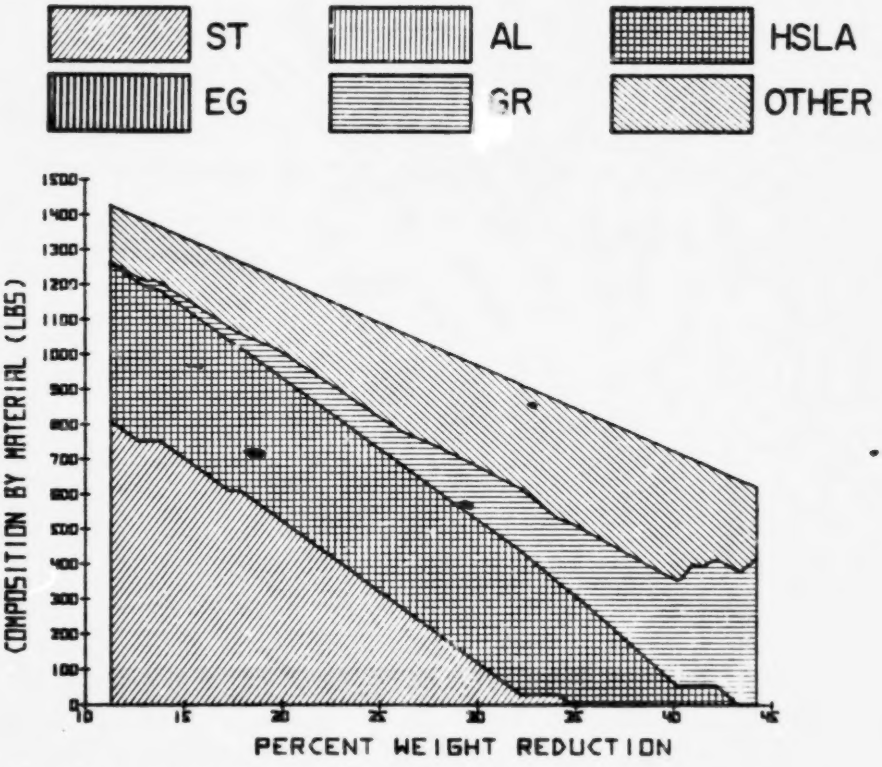


FIGURE 5 MATERIAL USAGE AND PERCENT WEIGHT REDUCTION (26 COMPONENTS, 9 MATERIAL MIXES, 1975 CHEVELLE)

weight is reduced 45%, all 26 components use graphite fiber in some form. The graphite usage increases substantially between the 42 and 45 percent levels since over this interval the only substitutions being made involve HSG and HMG as replacements for the hybrids. Figure 6 illustrates the weight-cost tradeoff for the 26 components at a graphite price of $6/pound ($13.20/kg). Figures 4 and 6 can be used together to simultaneously gauge material usage and manufacturing cost for a given level of weight reduction.

APPLICATIONS IN THE TRUCKING INDUSTRY

Background

Composite materials using graphite fibers show a great deal of promise in the trucking industry. As in the automotive application graphite will be used in body and functional parts of the vehicle. Graphite's high strength-to-weight and stiffness-to-weight ratios will allow design changes and weight reductions in trucks that will reduce their production and operational energy requirements. In addition trucks using graphite will be potentially more profitable. A brief overview of the trucking industry follows. The current production rate of heavy trucks is presented along with projections for motor trucking needs until 1995. A summary of some of the most likely applications of graphite composites within truck manufacture is presented and the technical advantages of using graphite composites in these applications are discussed. The economic incentives of graphite use for the truck operator are analyzed. In general, these advantages are increased payload and fuel efficiency. These are discussed within the context of several different types of trucking operations. Finally, specific applications of graphite truck components are examined.

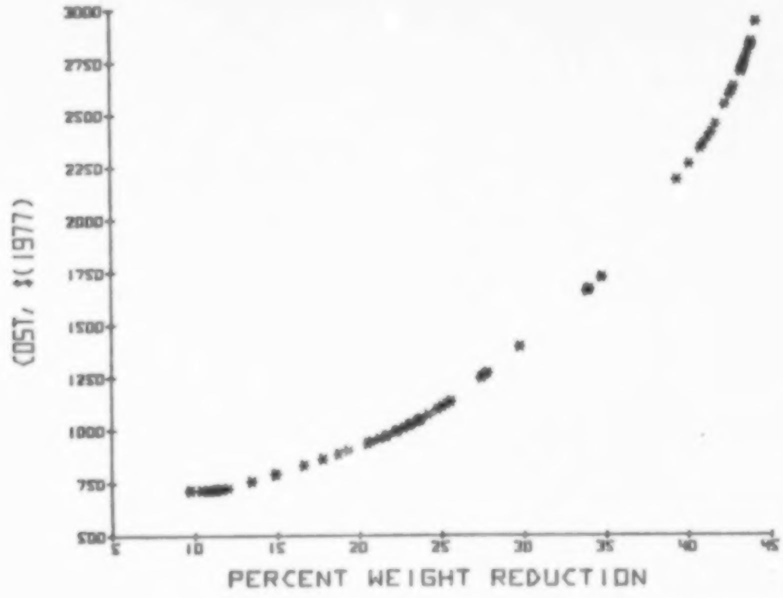


FIGURE 6 WEIGHT-COST TRADEOFF (26 COMPONENTS, 9 MATERIAL MIXES, 1975 CHEVELLE)

The trucking industry has been growing in terms of numbers of vehicles and volume of goods moved since its beginning about the turn of the century. The number of registered trucks almost doubled in the decade from 1968 to 1978 to a total in excess of 31 million [46]. Vehicle miles traveled by all trucks have also been constantly increasing since 1945, reaching 329,465 million miles in 1977 [47]. This figure represents a 7 percent increase from the previous year. In addition the average length of haul has been increasing. The average length of haul for Class 1 Intercity Common Carriers of General Freight was 457 miles per trip in 1977, which represents a 28 percent increase since 1970 [48].

It is projected that the U.S. demand for motor trucking services will continue to grow. In 1978 truck freight climbed to 609 billion ton-miles or 24.8 percent of all freight ton-miles. One study projects that this need may grow to 1,040 billion ton-miles by 1995 [49].

In order to meet this growing need, U.S. truck production and sales have been increasing. The total U.S. production of trucks and buses for 1978 was 3,722,567, which represents a 24 percent increase over the corresponding figure for 1976 [50].

Because of the increasing need for trucking services and the increasing fuel, labor and other costs associated with providing service, it is important to use trucks that are as efficient as possible. There are a number of ways to increase the efficiency of trucks and truck fleets including:

- Aerodynamic design changes
- Fleet management improvements
- Engine type and design changes
- Use of advanced lightweight materials
- Reduction of regulatory restrictions.

The use of graphite parts is one of many ways of improving truck efficiency. Several possible applications for the use of composite parts are discussed in the following section.

Potential Applications for Graphite Composites in the Trucking Industry

Because graphite composites have extremely high strength-to-weight and stiffness-to-weight ratios, they are being considered for a broad range of applications in both lightweight and heavy-duty trucks. Some parts have been made on an experimental basis and in low volume production programs. From the findings of these applications it appears that composite parts can provide a number of technical and economic advantages. The economic incentives to the truck owner are described further on. The following paragraphs briefly describe some of the technical and production advantages as well as some specific parts that are likely candidates for composite materials.

Several truck manufacturing companies have been testing the use of composite materials. These companies include among others:

- International Harvester
- Chevrolet
- Ford

- GMC
- Kenworth
- Mack
- Peterbilt
- Scania
- White
- Volvo.

While not all of these companies have experimented with graphite fibers, per se, they are developing the capability and design techniques necessary to convert to graphite and other composites. While near-term plans do not exist to replace steel and aluminum stamped parts, some clear advantages of composites have been cited.

International Harvester estimates that 50 percent less energy will be required to manufacture trucks using composites than is currently used [51]. This reduction is attributable in part to the facility changes that would be possible in the composite plant. Such facilities would require lower ceilings, lighter equipment and reduced warehousing space as compared to the current type of facility. Other energy savings would be possible in the following operations:

- Painting
- Phosphatizing
- Cleaning
- Washing.

For instance a composite part can be painted at a lower temperature than a metal part can be; therefore, less energy is required for the painting operation.

Another production advantage that has been noted is that the use of composite materials allows design changes and a reduction in the number of parts. Figure 7 shows the 13 major subcomponents of a composite truck cab. These 13 parts replace 85 parts in a conventional cab. Figure 8 shows other examples of design changes that are feasible when composites are substituted for steel in springs, drive shafts and suspension arm assemblies.

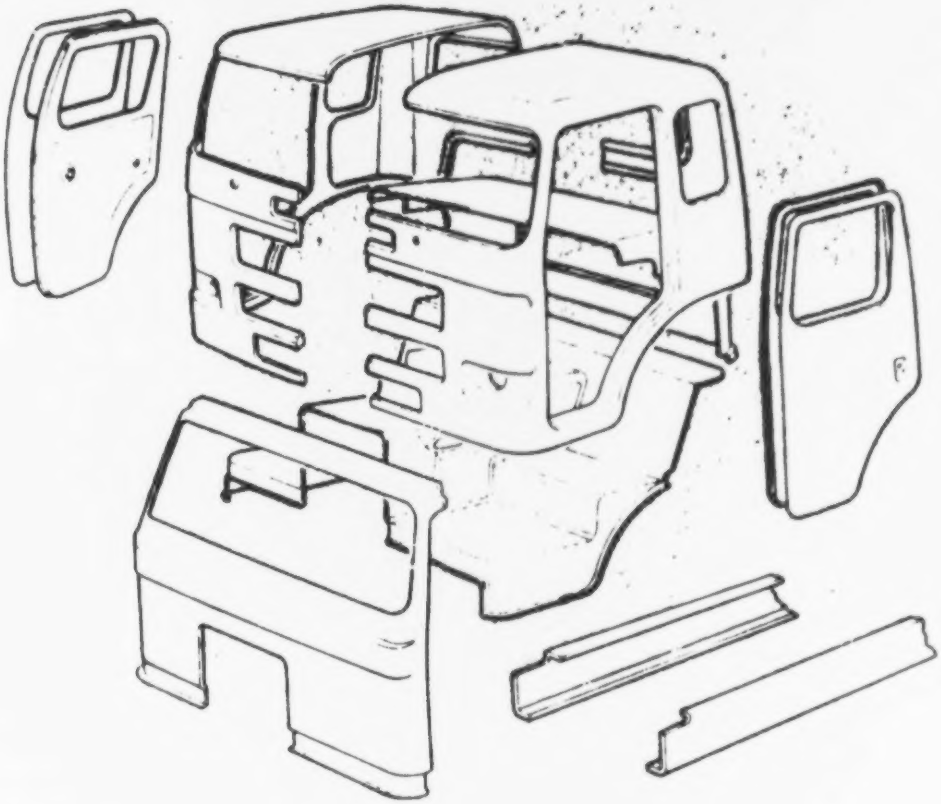
Table 30 presents some examples of weight-saving composite designs and the percent improvement in weight.

The Economic Incentives

The use of graphite composite material in trucks will make them lighter. Because of this, owners or operators of trucks made with graphite could realize one of two types of economic advantages. They will be able to improve fuel efficiency and/or they will be able to increase the payload of the vehicle.

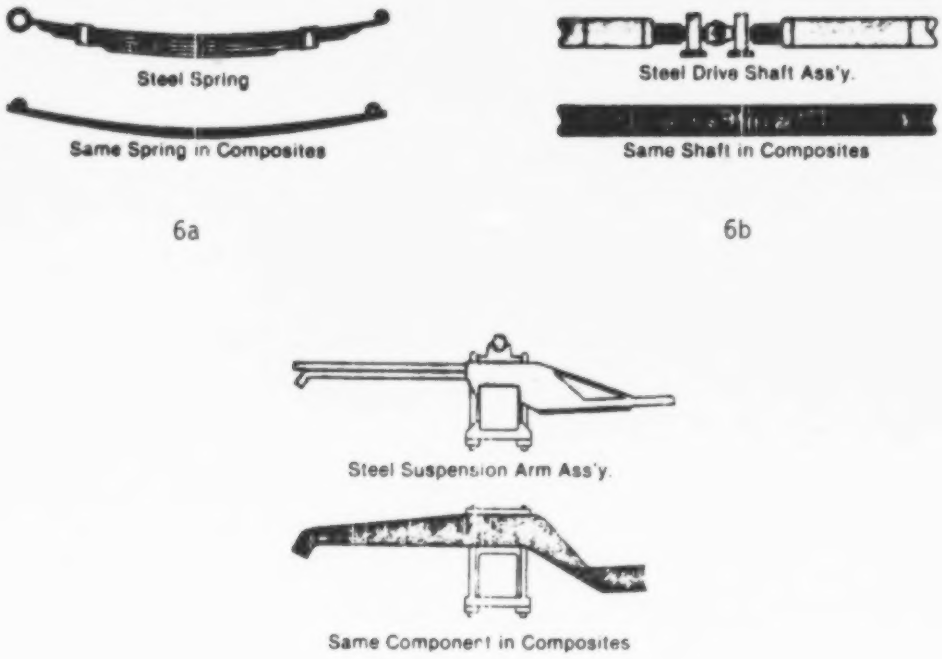
Increasing Fuel Efficiency--

The fuel consumed by the trucking industry as a whole has been increasing. This is in part due to the increase in vehicle miles traveled. In 1977, 37,964 million gallons of fuel were consumed by U.S. trucks over 329.5 billion miles, leading to an average consumption of 1,284 gallons per vehicle [52].



SOURCE: J. L. BAUER, A REVIEW OF COMPOSITE MATERIAL APPLICATIONS IN THE AUTOMOTIVE INDUSTRY FOR THE ELECTRIC AND HYBRID VEHICLE, PREPARED FOR THE U.S. DEPARTMENT OF ENERGY, OFFICE OF TRANSPORTATION PROGRAMS BY THE JET PROPULSION LABORATORY, PASADENA, CALIFORNIA, 1978, PP. 5.8.

FIGURE 7 MANUFACTURE OF TRUCK CAB USING ONLY 13 MAJOR COMPOSITE SUBCOMPONENTS COMPARED TO 85 FOR METAL


Steel Spring
Same Spring in Composites
Steel Drive Shaft Ass'y.
Same Shaft in Composites
Steel Suspension Arm Ass'y.
Same Component in Composites

6a 6b

6c

SOURCE: "ADVANCED COMPOSITES IN AUTOMOTIVE PARTS," ROCKWELL INTERNATIONAL, SP-7925, 1979.

FIGURE 8 DESIGN EXAMPLE CHANGES AVAILABLE WITH THE USE OF COMPOSITE MATERIALS

TABLE 30 EXAMPLES OF WEIGHT-SAVING DESIGNS IN COMPOSITES

COMPONENT	CONVENTIONAL DESIGN		COMPOSITE DESIGN		PERCENT IMPROVEMENT
	LB	KG	LB	KG	
HEAVY TRUCK DRIVE SHAFT	139	63	69	31	50%
LIGHT TRUCK DRIVE SHAFT	33	15	18	8	45%
TRUCK FRAME CROSS MEMBER	15	7	6	3	60%
TRUCK FRAME RAIL	259	118	127	58	51%
TRAILER AXLE HOUSING	294	134	205	93	30%

SOURCE: "ADVANCED COMPOSITES IN AUTOMOTIVE PARTS," ROCKWELL INTERNATIONAL, SP-7926, 1979.

Retail fuel prices for diesel fuel and regular gas have also risen sharply in recent years. Between the last quarter of 1975 and the first quarter of 1979, the average price of diesel fuel per gallon rose by 26 percent (to \$.654), while gasoline prices rose by 18.5 percent (to \$.719) [53]. In large measure as a result of fuel price increases line-haul costs are absorbing a larger portion of revenue dollars. Table 31 shows the distribution of the revenue dollar among costs and operating revenues for 1974 through 1977. Because fuel consumption and prices are both rising, fuel efficiency is becoming an economic consideration of increasing importance.

In order to calculate the economic incentive due to increases in fuel efficiency brought about by the use of composites, the tare weight reduction is determined. This reduction is examined as a function of the gross combination weight of the vehicle. This method of calculating economic incentives for graphite use assumes that the truck operator will not use the reduction in tare weight to increase the payload of the vehicle. A number of studies have been undertaken to establish the relationship between fuel consumption and total combination vehicle weight. The results of six such studies are presented in Figure 9 and are considered more accurate than the figures which could be derived from the national statistics mentioned earlier. The best-fit equation for the Freightliner Corporation results is as follows:

Gallons per mile = 0.1387 + 0.000001450 gross combination weight [54]

The amount of fuel saved is then multiplied by the number of miles traveled by the truck in a year and the cost of fuel to determine the annual cost reduction per vehicle. Thus according to this fuel consumption equation, every pound tare weight saved will result in a fuel savings of 0.00000145 gallons per mile. If a vehicle travels 120,000 miles per year and the price of fuel is \$1.40 per gallon, the annual cost savings per vehicle is \$.24 per pound saved. If for example the total weight of the truck was reduced by a total of 2,000 pounds by using graphite composite components, the annual cost savings due to improvements in fuel efficiency would be \$243.60 per vehicle.

TABLE 31 DISTRIBUTION OF THE REVENUE DOLLAR IN MOTOR CARRIER OPERATIONS FOR ALL CARRIERS, 1974-1977

YEAR	LINE-HAUL	PICKUP DELIVERY	BILLING & COLLECTING	PLAT-FORM	TERMINAL	MAIN-TENANCE	TRAFFIC & SALES	INSURANCE &SAFETY	GENERAL & ADMINI-STRATIVE	NET OPERAT-ING REVENUE
1974	52.8 ¢	15.5 ¢	1.6 ¢	7.8 ¢	7.1 ¢	1.9 ¢	2.3 ¢	0.9 ¢	5.4 ¢	4.7 ¢
1975	53.1	15.2	1.6	7.2	7.7	1.8	2.5	0.9	5.7	4.3
1976	52.8	15.3	1.7	7.7	7.5	1.7	2.5	0.8	5.1	4.9
1977	53.5	14.9	1.7	7.6	7.8	1.7	2.3	0.8	4.5	5.7

SOURCE: AMERICAN TRUCKING TRENDS 1977-1978, AMERICAN TRUCKING ASSOCIATIONS, INC., DEPARTMENT OF RESEARCH AND STATISTICAL SERVICES, WASHINGTON, DC, 1978, P. 18.

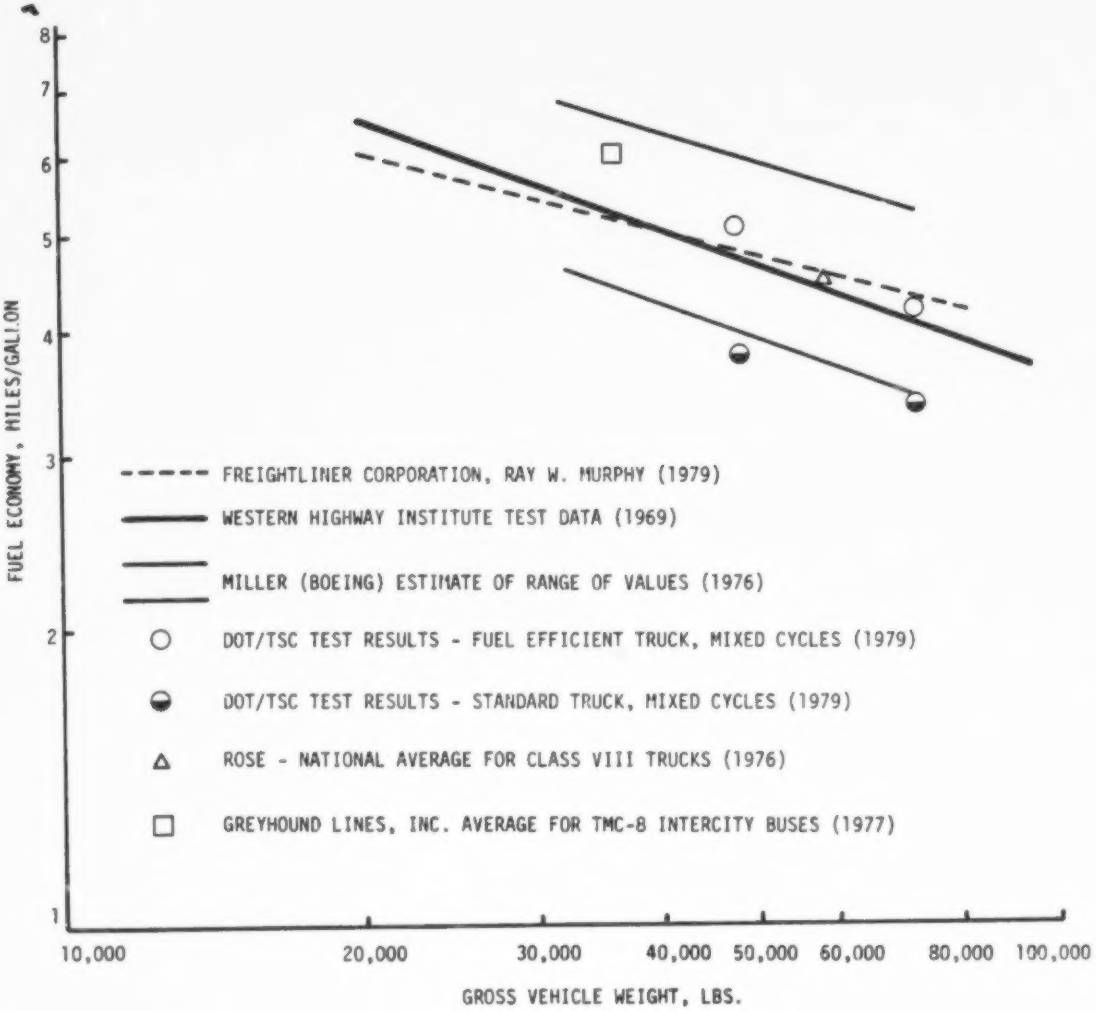


FIGURE 9 FUEL ECONOMY OF TRUCKS AND BUSES AS A FUNCTION OF GROSS VEHICLE WEIGHT

Increased Payload--

Currently there are no fuel efficiency standards for heavy trucks. Therefore the only incentive for truck operators to improve fuel efficiency is the potential cost savings just described. However the total gross weight of vehicles and their payloads are regulated by each state. Table 32 presents the maximum allowable vehicle weights by state. If graphite components reduce the weight of the vehicle itself, the operator can choose to increase the weight of his payload by the same amount. If more payload can be carried by the truck, potential revenue increases or line haul cost reductions can be realized. A carrier that is a common carrier or other carrier that offers its services on a "for hire" basis can increase its revenues by using lighter weight trucks. A private carrier or one that is owned by a company that runs its own line haul equipment can reduce its operating costs. The following paragraphs describe a technique used in calculating the magnitude of these potential increased revenues or decreased costs to the individual carrier. Both of these models are attributable to the Freightline Corporation [54].

Increased Revenue--There are a number of reasons why "for hire" carriers do not always operate at the full legal gross combined vehicle weight. These include:

- Lack of available cargo to fill trucks on required schedule
- One-way cargoes or a preponderance of cargo moving in one direction
- Lack of space, i.e., the volume of the vehicle is filled before the legal weight limit is reached
- Loose packing due to fragile or awkwardly shaped cargo
- Need for trailers, tractors or drivers at other points of the carrier's service
- Economic restrictions such as prohibitive costs of loading and unloading.

Because of these constraints, an operator cannot necessarily increase the payload by one pound for every pound saved in vehicle weight. In addition a large carrier operation which utilizes a number of trucks to service a single location may be able to pick up the cargo left over from one vehicle with a subsequent vehicle and thus not lose potential revenue. A small operator would not have the option of picking up the additional cargo with a subsequent vehicle.

In general the average increased revenue that a "for hire" carrier can realize from reduced tare weight can be computed using the following formula:

$$H = \frac{F*M*T*P}{2000}$$

where

H = Increased revenue, dollars per vehicle per year
F = Freight rate, dollars per ton-mile
M = Miles traveled per year by the vehicle
T = Percent of trips at the full legal weight
P = Pounds reduced tare weight.

Using this method, a general commodities carrier that was operating on a "for hire" basis would be able to increase its revenues by $0.549 per pound of tare weight reduced as follows:

TABLE 32 MAXIMUM MOTOR TRUCK HEIGHTS, WIDTHS AND WEIGHTS BY STATES, MARCH 12, 1979

STATE	MAXIMUM VEHICLE HEIGHT FT.-IN.	MAXIMUM VEHICLE WIDTH INCHES	SINGLE AXLE INTERSTATE	TANDEM AXLE INTERSTATE	GROSS COMB. WEIGHT INTERSTATE
ALABAMA	13-6	96	20,000	40,000	80,000
ALASKA**	13-6	96	20,000	34,000	NO INTERSTATE
ARIZONA	14*	96	20,000	34,000	80,000
ARKANSAS	13-6	96	18,000	32,000	73,280
CALIFORNIA	14*	96	20,000	34,000	80,000
COLORADO	13-6*	96	20,000	36,000	80,000
CONNECTICUT	13-6	102	22,400	36,000	73,000
DELAWARE	13-6	96	20,000	40,000	80,000
DIST. OF COL.	13-6	96	22,000	38,000	73,280
FLORIDA	13-6	96	20,000	40,000	80,000
GEORGIA	13-6	96	20,340	40,700	80,000
HAWAII	13-6	108	24,000	34,000	80,800
IDAHO	14	102	20,000	34,000	80,000
ILLINOIS	13-6	96	18,000	32,000	73,280
INDIANA	13-6	96	18,000	32,000	73,280
IOWA	13-6	96	18,000	32,000	73,280
KANSAS	13-6	96	20,000	34,000	80,000
KENTUCKY	13-6*	96	20,000	34,000	80,000
LOUISIANA	13-6	96	20,000	34,000	80,000
MAINE	14SR	102	22,000	34,000*	80,000
MARYLAND	13-6	96	22,400	40,000SR	73,280
MASSACHUSETTS	13-6	96	22,400	36,000	80,000
MICHIGAN	13-6	96	20,000*	34,000*	80,000
MINNESOTA	13-6	96	20,000*	34,000*	80,000
MISSISSIPPI	13-6	96	18,000	32,000	73,280
MISSOURI	13-6	96	18,000	32,000	73,280
MONTANA	13-6	102	18,000*	32,000*	80,000
NEBRASKA	14-6	96	18,000*	32,000*	73,280
NEVADA	14	96	20,000	34,000	80,000
NEW HAMPSHIRE	13-6	96	22,400	36,000	80,000
NEW JERSEY	13-6	96	22,400	34,000	80,000
NEW MEXICO	13-6	96	21,600	34,320	86,400
NEW YORK	13-6	96	22,400	36,000	80,000
NORTH CAROLINA	13-6	96	19,000	36,000	79,800
NORTH DAKOTA	13-6	96	20,000	34,000	80,000
OHIO	13-6	96	20,000	34,000	80,000
OKLAHOMA	13-6	96	20,000	34,000	80,000
OREGON	13-6	96	20,000	34,000	80,000
PENNSYLVANIA	13-6	96	22,400	36,000	73,280
RHODE ISLAND	13-6	102	22,400	36,000	80,000
SOUTH CAROLINA	13-6	96	20,000	36,000	80,000
SOUTH DAKOTA	13-6	96	20,000	34,000	80,000
TENNESSEE	13-6	96	18,000	32,000	73,280
TEXAS	13-6	96	20,000	34,000	80,000
UTAH	14	96	20,000	34,000	80,000
VERMONT	13-6	102	22,400	36,000	80,000
VIRGINIA	13-6	96	20,000	34,000	78,000*
WASHINGTON	14	96	20,000	34,000	80,000
WEST VIRGINIA	13-6*	96	20,000	34,000	80,000
WISCONSIN	13-6	96	20,000*	34,000*	80,000
WYOMING	14	102	20,000	36,000	80,000
FEDERAL INTERSTATE MAXIMUMS	N.S.	96 VEH. 102 BUSES	20,000	34,000	80,000

*DESIGNATED HIGHWAYS, OR BY PERMIT ONLY.

**NO INTERSTATE HIGHWAYS.

SR-SPECIAL RESTRICTIONS
N.S.-NOT SPECIFIED

NOTE: ABOVE FIGURES DO NOT INCLUDE TOLERANCES

SOURCE: MVMA MOTOR VEHICLE FACTS AND FIGURES 1979, MOTOR VEHICLE MANUFACTURERS ASSOCIATION OF THE UNITED STATES, INC., DETROIT, MICHIGAN, 1979.

$$R = \frac{\$0.136}{\text{ton-mile}} * \frac{120{,}000\text{ miles}}{\text{year}} * \frac{8}{100}\text{ trips at full legal weight} *$$

$$\frac{\text{ton}}{2000\text{ lbs.}} * \text{ 1 pound reduction in tare weight.}$$

In order to determine the incentive to the operator to reduce tare weight, one must look further than revenue changes to increases in profit. As an example, if tare weight were to be reduced 68 pounds per spring by the introduction of graphite leaf springs, a vehicle might save 272 pounds (two springs * two axles). This would result in increased revenues of $149.33 per vehicle per year. Of this increased revenue about 50 percent would be spent in additional soliciting, handling and terminal costs associated with the incremental cargoes. In addition a large carrier would have been able to capture 50 percent of this increased revenue by use of subsequent vehicles without reduced tare weight [54]. Therefore, for the average truck in general carrier service described above, the annual increased profit from reduced tare weight associated with the use of composite leaf springs would be $37.33.

This increased revenue (or profit) per pound reduction in tare weight is highly specific to the nature of the particular operator. A small carrier of bulk commodities that traveled only 90,000 miles per year with 50 percent of all trips at full legal weight but did not have the opportunity to make pickups with subsequent vehicles might expect to show $416.16 increased annual profits for the use of the same [54] graphite leaf springs.

After computing this figure, the operator will proceed with the decision process used for capital investment planning. The practices for making such decisions vary from company to company but usually consider the following factors:

- Pay-out period
- Rate of return on investment
- Interest expense associated with borrowed capital
- Income tax rate
- Depreciation
- Maintenance
- Residual value
- Investment tax credits
- Net present value of weight-saving components. [55]

Assuming a five-year life, 20 percent return on investment and a 10 percent interest rate, the large general commodities carrier could profitably pay about an extra $130 for the graphite springs over the traditional leaf springs on a pre-tax basis, while the small bulk commodity carrier could conceivably pay about an additional $460 for the same tare weight reduction.

Cost Avoidance--Since many vehicles are owned and/or operated by the company requiring the transportation of goods, this increased revenue calculation of the value of reduced tare weight is not appropriate for all vehicles. For these private carriers the operator realizes increased profits by reducing operating costs. Reduced tare weight can mean increasing the amount of cargo transported in a single vehicle trip and thus a reduced number of trips and possibly a reduction in the number of vehicles in the fleet. As with the "for hire" examples, wages, fuel cost and maintenance costs remain the same if payload is increased to the full legal weight. Also as described above, terminal and handling are still incurred for all of the goods transported.

The reduced operating cost for the private carrier due to reduced tare weight can be calculated as follows [54]:

$$S = \frac{C * M * T * E * (1.0 - X - R) * P}{L}$$

where:

S = Cost savings, dollars per vehicle per year
C = Operating cost, dollars per mile
M = Miles operated per year
T = Percent of trips limited by legal weight
E = Life of equipment
X = Return on investment
R = Interest rate
P = Number of pounds reduced tare weight
L = Payload, pounds.

A typical private bulk carrier of petroleum might travel 150,000 miles per year with 50 percent of its trips limited by weight. Using an operating cost of $0.48 per mile, a six-year life, payload of 50,000 pounds (22,727 kg), interest rate of 10 percent and return on investment of 20 percent, a cost savings of about $1,290 per vehicle might be realized by using the same graphite leaf springs on a pre-tax basis. In this example the operator would also realize the increased fuel efficiency benefits on that half of his trips that the vehicle traveled empty.

Materials Substitution Cost Example

Leaf springs for trucks appear to be one of the most likely automotive applications of carbon fiber composites. In this application it is possible to use a unidirectional composite, so that a carbon fiber leaf spring that is functionally equivalent to a steel leaf spring assembly will only weigh 20 percent as much as the steel leaf spring assembly. As one example [56], Rockwell International has developed a one leaf carbon epoxy leaf spring for a heavy truck that is functionally equivalent to a five leaf steel spring that weighs 85 lbs (39 kg). The carbon-epoxy spring only weighs 17 lbs (8 kg). In this instance replacement of four steel spring assemblies by four carbon leaf springs would result in a direct weight savings of 272 lbs (124 kg). for the vehicle.

Manufacture of Carbon Leaf Spring--

Process Description--Carbon fiber leaf springs could be manufactured by a number of alternate fabrication techniques. These alternate methods include:

1. Layup of precut prepreg layers followed by compression molding.
2. Filament winding of a cylindrical fiber composite on a large mandrel. Blanks are then cut in the circumferential direction, and then shaped and cured.
3. Pultrusion followed by post-forming, either on line with the pultrusion operation or as a separate operation.

For purposes of this study it was assumed that a blank of the approximate shape of the spring is first pultruded to a B stage of polymerization. The blanks are then cut to length and compression molded to their final shape.

In the pultrusion process continuous filaments are drawn through a resin bath for impregnation, and then pulled through a heated, hardened steel die. The die orients the reinforcement, sets the final shape of the laminate and controls its resin content. The consolidated composite may be fully, or only partially, cured within the die. In the latter case, the composite can be post formed to form curved components or components of variable cross-sectional area. Many structural shapes such as I-beams, channels, wide flange beams and sheets can be pultruded [57, 58, 59]. The continuous nature of the process allows for the production of long pieces which can be cut to any desired length with flying cutoff saws in which the saw table moves with the pultrusion as it is being cut. Depending on the required cure time and section thickness, pultrusion speeds through the die may range from two inches per minute to 100 inches per minute.

Compression molding starts with the placement of a predetermined amount of a deformable resin-reinforcement mixture in the lower half of a set of preheated matched metal molds. These molds have a close fitting telescoping area to seal the plastic component and to trim the reinforcement when the mated halves are brought together by the platens of the compression press. As the mold is closed, the pressure rises in the mold and the charge material flows to fill the cavity. Depending on the characteristics of the molding compound, the process may range from 200 psi to 3,000 psi. Molding temperatures may range from 250°F to 320°F. Required residence time in the mold may range from about one to 30 minutes depending on the resin formulation and on the thickness, size and shape of the molded part. Upon completion of the molding operation, the part is removed from the mold. Any flash due to leakage of material through the gap between the mated mold halves is trimmed, and the part is forwarded to a secondary fabrication or assembly operation as required. Fesko, Mellick and Newman [60] discuss in more detail the issues and problems concerning the fabrication of automotive composites by compression molding.

Manufacturing Cost Analysis--

1. General Assumptions: It will be assumed that the facility will be capable of producing 96,000 graphite-polyester leaf springs per year, that each weigh 17 lbs (8 kg). The springs will be approximately five feet long and will have an average cross section of approximately six square inches (approximately three inches wide by two inches high). In addition to material losses in fabrication of 15 percent, 5 percent of the final product will be rejected and will be scrapped.
2. Material Requirements: It will be assumed that the leaf spring will contain 60 percent by volume high strength (30×10^6 psi) carbon fiber and 40 percent by volume polyester resin. On a weight basis this corresponds to 65.6 percent by weight carbon fiber and 34.4 percent by weight resin. Based on a 1977 resin cost of \$0.46/lb. (\$1.00/kg) [61], the unit price of raw materials, C_{RM}, is related to the unit price of carbon fiber, X, by the following equation:

$$C_{RM} = 0.08 + 0.224\,X \quad (\$/kg)$$

Taking into account material losses and scrappage rate, approximately 20 pounds (9 kg) of raw materials have to be purchased for every 17 pound (8 kg) spring sold. The raw material costs, C_{RMS} per spring shipped is therefore:

$$C_{RMS} = 3.40 + 9.84X \quad (\$)$$

3. Fabrication Cost Estimates:
   a. Pultrusion--If a pultrusion rate of two feet per minute is assumed for the production of the molding blanks, 2.5 minutes of machine time will be required to form a 5 foot blank. 192 blanks can be produced in one eight-hour shift. With 5 percent scrappage, 100,800 blanks are required to produce 96,000 springs. The production rate will require operation over 525 shifts per year if one pultruder is used. This production level can be achieved with a single pultruder operating two shifts per day, five days per week, with an occasional day shift on Saturdays to allow for maintenance downtime. Labor requirements would be one operator assisted by a half-time creel loader. The principal other variable cost factor would be electricity to operate the pultuder, the saw and to heat the die to partially cure the resin. Based on the current costs of operating extruders [62, 63, 64], it is estimated that an installed pultruder would require a capital investment of approximately $125,000. Tooling costs would entail $5,000 for the pultrusion die which was assumed would be good for 200,000 feet of operation. Cost of fabricating the pultruded blanks are summarized in Table 33. Unit labor and electricity rates were those prevailing in the automobile industry in 1977. Fixed cost assumptions are self-explanatory.
   b. Compression Molding--Because compression presses are not designed with a high length to width ratio, it was assumed that multi-cavity molds would be used. For purposes of this cost calculation, it was assumed that a two-cavity mold would be used. There is a close correlation between the size (or weight) of the items being molded and the cost of the molding press and the matched metal molds. The cost of the molds also depends on the complexity of the item being produced, since this establishes the amount of machining time required to fabricate the mold. In a 1973 paper, Sanada proposed the following relation for the main machine cost for compression molding operations [65]:

      Log (main machine cost, $) =

      0.61 log (total part weight, lb.) + 4.40

      Adjusting for inflation, the above expression in 1977 dollars becomes:

      Log (main machine cost, $) =

      0.61 log (total part weight, lb.) + 4.70

TABLE 33 FABRICATION COST OF PULTRUDED LEAF SPRING BLANK*

	FABRICATION COST $/HR
VARIABLE FABRICATION COST	
LABOR, 1.5 OPERATORS @ $12.60/HR	$18.90
UTILITIES, 70 KWH @ $0.03/KWH	2.10
SUBTOTAL	21.00
FIXED FABRICATION COST (CAPITAL INVESTMENT = $125,000)	
DEPRECIATION (20 PERCENT OF CAPITAL INVESTMENT/YR)	5.97
AMORTIZATION OF TOOLING (200,00 FT. LIFE, $5000 TOOLING INVESTMENT)	3.00
GENERAL PLANT OVERHEAD (60 PERCENT DIRECT LABOR)	11.34
SUBTOTAL	20.31
TOTAL FABRICATION COST	41.31
FABRICATION COST PER BLANK	$1.72
FABRICATION COST PER BLANK (INCLUDING 5 PERCENT SCRAPPAGE)	$1.81

*DIMENSIONS: 5 FT. LONG X 3 IN. WIDE X 2 IN. THICK
PRODUCTION RATE: 24 BLANKS/HR.

In a prior study by the authors [66], the following correlation for the cost of tooling for a compression molded part of simple shape (such as a leaf spring) as a function of part weight was developed

$$\text{Log (mold cost, \$)} = \text{Log (part weight, lb.)} + 3.60$$

Based on the above equations, assuming a 40 lb charge for two springs, it was estimated that a compression press would cost $475,000 and the mold set would cost $160,000.

Based on a residence time estimate of one minute per 0.1 in part thickness, it was estimated that curing a spring with a maximum cross section of 2 inches would require a 20 minute residence time in the mold. Thus a press with a two-cavity mold could produce six springs per hour or 48 springs per shift. To maintain the desired production output, it is necessary to be able to mold 192 springs per shift. Thus, with the operating assumptions used, four compression presses will be required. (Note: If four-cavity molds had been assumed, only two presses, but of higher capacity, would have been required.)

Assuming 20 percent installation costs, the total capital investment required for the molding operation would be $2.3 million for the presses and $640,000 for the molds.

The operating cost summary for the molding operation is summarized in Table 34. In this estimate it was assumed that each press would

TABLE 34 FABRICATION COST OF CARBON-COMPOSITE LEAF SPRING MOLDING OPERATION*

	FABRICATION COST $/HR
VARIABLE FABRICATION COST	
LABOR, 8 OPERATORS @ $ 12.60/HR	$100.80
UTILITIES, 160 KWH/PRESS X 4 X $0.03/KWH	19.20
SUBTOTAL	120.00
FIXED FABRICATION COST (CAPITAL INVESTMENT: $2.3 MILLION)	
DEPRECIATION (20 PERCENT OF CAPTIAL INVESTMENT/YR)	114.00
AMORTIZATION OF MOLDS (200,00 UNITS/MOLD)	19.20
GENERAL OVERHEAD @ 60 PERCENT OF DIRECT LABOR	60.48
SUBTOTAL	193.68
TOTAL FABRICATION COST	313.68
FABRICATION COST PER SPRING	$13.07
FABRICATION COST PER SPRING INCLUDING 5 PERCENT SCRAPPAGE	$13.72

*PRODUCTION RATE: 24 SPRINGS/HR IN FOUR TWO-CAVITY MOLDING PRESSES.

require two operators. Utilities are mainly the cost of electricity to heat the platens. Other direct costs include steel ring inserts for the ends of the springs to provide additional strength for fastening. These are treated as additional material costs, and are not included in Table 34.

c. Cost Summary--The total estimated manufacturing cost for carbon fiber composite leaf springs are summarized in Table 35. Note that carbon fiber costs predominate with fiber prices of $2 a pound or

TABLE 35 MANUFACTURING COST SUMMARY--CARBON FIBER LEAF SPRING

	$/LEAF SPRING
MATERIALS	
CARBON FIBER AND RESIN (X=UNIT PRICE OF CARBON FIBER)	3.40 + 9.84X
STEEL INSERTS	0.50
SUBTOTAL	3.90 + 9.84X
FABRICATION COSTS	
PULTRUSION	1.81
COMPRESSION MOLDING	13.72
SUBTOTAL	15.53
TOTAL MANUFACTURING COSTS (INCLUDING 5 PERCENT SCRAPPAGE)	19.43 + 9.84X

EXAMPLE: IF CARBON FIBER PRICE IS $10/LB ($4.55/KG), MANUFACTURING COST IS $117.83 PER SPRING.

more with the assumed manufacturing sequence. The fabrication costs could vary by $5 per unit depending on this sequence.

Manufacture of Metal Leaf Spring--

The cost of manufacture of a five-leaf truck spring was based on a cost analysis for a five-leaf spring for a Ford Pinto Automobile published in a study for the U.S. Department of Transportation [67]. Cost details for the automobile spring from the referenced study are presented in Table 36. The examination of the data in this table indicates that the cost elements can be classified into two main subgroups: a) the metal leaves--the first five line items and b) accessories and assembly--the balance of the items in the table. The cost elements of the metal leaves can be broken down into a weight-dependent group which, based on the cost of leaf No. 5, was assumed to be $0.21/lb. ($0.10/kg), and a weight independent group. The accessory and assembly costs appear to be weight independent.

Reorganizing the data in Table 36, the cost of a five-leaf spring assembly, C_{SA}, can be expressed as:

$$C_{SA} = 0.21W + 5.62 \quad (\$)$$

where W = weight of leaves.

In the case of the Pinto, where W = 22.36 lbs. (10.16 kg), the cost of a spring is $10.32. Assuming that this expression is also valid for heavier spring assemblies, it can be used to estimate the cost of a five leaf truck spring such as the one given in the Rockwell International example. Based on a spring assembly weight of 85 lbs. (39 kg), and assuming that the leaves represent 95 percent of the assembly weight, it is estimated that the 85 lb (39 kg). truck leaf spring would cost

$$(0.95)(85)(0.21) + 5.62 \text{ or } \$22.58 \text{ per assembly.}$$

The cost of this assembly, in 1977 dollars, would be approximately 20 percent higher or $27.10.

The above cost calculations are based on a production volume sufficient to support the manufacture of 250,000 vehicles. The spring manufacturing rate is thus 500,000 spring assemblies per year. This is five times the production volume assumed for the carbon fiber reinforced plastic leaf spring. It is to be noted that with the production sequence assumed, increasing the carbon fiber production level would require the installation of parallel lines so that production costs would not change significantly as a function of output above 100,000 springs.

MISCELLANEOUS APPLICATIONS

Industrial Applications

Advanced composite components are currently being evaluated for a broad range of industrial machinery which have high speed moving parts. Textile machinery has been the focus of much attention. The use of graphite composites on various components of fly shuttle weaving looms has increased the performance of the looms. The benefits of light weight, stiffness, fatigue resistance and noise reduction have led to higher productivity and reduced downtime. Picking sticks are the levers that drive

TABLE 36 MANUFACTURING COST DETAILS FOR A FIVE-LEAF STEEL SPRING

ITEM	REQ'D PER VEHICLE	MATERIAL	WEIGHT	TOTAL TOOLING ($000)	YEARS AMORT.	COST PER VEHICLE		
						VARIABLE	FIXED	TOOLING
LEAF - REAR SPRING MAIN	2	STEEL	19.40	55.0	6	6.1378	0.0000	0.0262
LEAF - REAR SPRING #2	2	STEEL	10.90	15.0	6	3.8076	0.0000	0.0071
LEAF - REAR SPRING #3	2	STEEL	7.78	15.0	6	3.1572	0.0000	0.0071
LEAF - REAR SPRING #4	2	STEEL	4.46	15.0	6	2.4894	0.0000	0.0071
LEAF - REAR SPRING #5	2	STEEL	2.18	--	--	0.4580	0.0000	--
SUBTOTAL--LEAVES	--	--	44.72	100.0	--	16.0500	--	0.0550
INSULATOR - REAR SPRING LEAF	10	PLASTIC	0.20	25.0	6	0.1680	0.0000	0.0119
BOLT - REAR SPRING LEAF CENTER	2	STEEL	0.18	5.0	6	0.0676	0.0000	0.0024
NUT - REAR SPRING LEAF CENTER BOLT	2	STEEL	0.06	--	--	0.0250	0.0000	--
CLIP - REAR SPRING LEAF (4 LEAF)	2	STAMPED STEEL	0.35	10.0	6	0.0894	0.0000	0.0048
CLIP - REAR SPRING LEAF (3 LEAF)	2	STAMPED STEEL	0.32	10.0	6	0.0856	0.0000	0.0048
CLIP - REAR SPRING LEAF (2 LEAF)	2	STAMPED STEEL	0.31	10.0	6	0.0814	0.0000	0.0048
PAD - REAR SPRING LEAF CLIP	6	RUBBER	0.12	1.0	6	0.1722	0.0000	0.0014
ASSEMBLY - REAR SPRING FRONT BUSHING	2	RUBBER + STEEL	1.52	34.5	6	0.8438	0.0000	0.0164
PLATE - REAR SPRING SHACKLE	4	STEEL	1.02	10.0	6	0.2612	0.0000	0.0048
BOLT - REAR SPRING SHACKLE	4	STEEL	0.84	6.0	6	0.8720	0.0000	0.0029
NUT - REAR SPRING SHACKLE BOLT	4	STEEL	0.08	--	--	0.0360	0.0000	--
BUSHING - REAR SPRING SHACKLE	8	RUBBER	0.32	20.0	6	0.2960	0.0000	0.0095
BRACKET - REAR SPRING SHACKLE MTG.	2	STAMPED STEEL	2.48	13.0	6	0.6622	0.0000	0.0062
ASSEMBLY OF REAR SPRING ASSEMBLY	2	--	52.52	9.0	6	0.7934	0.1244	0.0043
SUBTOTAL--REAR SPRING ASSEMBLY	--	--	52.52	225.5	--	20.5038	0.1244	0.1217

SOURCE: M. R. HARVEY AND D. J. CHUPINSKY, "DEVELOPMENT OF A MOTOR VEHICLE MATERIALS HISTORICAL HIGH-VOLUME INDUSTRIAL PROCESSING RATES DATA BANK (COMPACT TYPE CAR)," REPORT, DOT-HS-802066, NTIS REPORT PB-262-118, OCTOBER 1976.

shuttles back and forth in fly shuttle weaving looms. Picking sticks which are currently made of densified wood often fail after three to six months operation. Experimental picking sticks made of pultruded graphite weighed 65 percent less than wood which resulted in a 10 percent increase in loom speed and an operational life of up to three years; additionally a noise reduction of 3 dB was also reported [68]. Other textile machinery components under development include heddle frames, lay bars, flyer arms, needles, sinkers, guide bars and faller bars. However, the acceptance of the developments by the textile industry has been slow largely due to the depressed conditions of this industry and its hesitance to invest in new technology at a time when increases in production capacity are not required. Similar industrial development applications include arbors for cigarette packaging machines, components of paper making machines and copying machines.

These composite parts will be introduced slowly over the next decade as replacements for components made of standard materials, but total consumption of high performance fibers is not expected to be large. This projection would be sensitive to changes in regulations pertaining to noise in the workplace and, if OSHA noise regulations become more stringent, advanced composite components would become more available as they offer a means of significantly reducing (3 dB to 5 dB) the noise of large machine systems.

Chemical Plant Structures and Equipment

Advanced composites are starting to find specialized uses in chemical plant process equipment where corrosion resistance is of prime concern. For example a graphite fiber reinforced polyphenylene sulfide (PPS) valve was commercially introduced last fall by Babcock and Wilcox Co., Advanced Composites Department. The valve can be used interchangeably with alloy valves in piping systems for severely corrosive fluids--most bases and many acids in diverse concentrations--with temperatures from -40° F to 300° F and at line pressures of up to 200 psi. International Polymer Corp. makes graphite PPS bearings, piston rings and similar equipment that are also used in the chemical industry.

The use of fiberglass reinforced plastics (FRP) in the processing, transmission and storage of corrosive chemicals is well established and documented. FRP has served well in environmental protection and pollution abatement equipment such as scrubbers and neutralization tanks, platforms, walkways and safety railings in petroleum refineries and chemical plants. Currently about 10 percent of all FRP is consumed in such corrosion resistant applications [69].

The design of the larger pieces of equipment is controlled by the stiffness of the FRP. In some instances selective reinforcement of the structure with graphite fiber could be cost effective even at current prices for graphite. As the price of graphite decreases to less than \$20/lb (\$44/kg), the use of graphite/glass hybrids will increase in chemical plant structural equipment. Graphite composites will also find use in environments where FRP fails, particularly highly caustic solutions which attack and dissolve the glass fibers.

Since the use of advanced composites in chemical plant structures and equipment will be an evolution of existing FRP technology, development time will be compressed and the pacing items will be the cost of the high performance fibers. Uses of the hybrid composites will be established within the next five years and by 1990 graphite consumption should be of the order of 10 percent of the FRP consumption for corrosion resistant applications which is projected to be 230,000 metric tons (500 million pounds) in that year assuming an annual growth rate of 8 percent. The corresponding graphite fiber consumption in 1990 would be 23,000 metric tons (50 million pounds).

Agricultural Machinery

Farming is essentially a series of unit operations that have to be carried out over a precise schedule with only a narrow time window available for each operation. Each specific operation has to be successfully executed when due. There are severe economic penalties for not doing so--a poor yield or failure of the crop. Given the uncertainties of climate and weather, a farmer cannot afford to have a critical piece of equipment fail or be inoperative when it is required and thus he places a high premium on equipment reliability and on ease of repair.

Manufacturers of agricultural equipment are evaluating the potential of advanced composite components as a means of decreasing the cost or of increasing the productivity of farm equipment. Applications include components for self propelled equipment similar to the truck components discussed earlier in this section, namely drive shafts, leaf springs, support brackets, etc. Since traction increases with increasing system weight, the motivation for using advanced composites is not weight saving but lower manufaturing costs or better equipment performance in terms of longer life, better fatigue characteristics, higher reliability, lower maintenance, less corrosion, reduced inertia for better energy transmission and less noise.

Advanced composites are also being considered for use in a variety of drawn equipment such as seeders, tillers and harvesters. In terms of mechanized U.S. farming operations, the larger the machinery the higher the acreage that can be worked within a given period of time and with a given amount of labor. The width of many pieces of current agricultural machinery is currently limited by the weight of the machinery. The ultimate width of a piece of drawn machinery is determined by either the pulling capacity of the tractor that the farmer has available or by the load bearing capacity of the soil. If the equipment is too heavy it will sink into the soil and not perform properly. For example the widest piece of equipment made by one of the leading agricultural equipment manufactureres is a 31 foot (9.4 m) wide row crop cultivator. Harvesting platforms are 24 feet (7.2 m) or less in width. It is possible to conceive of equivalent equipment made of advanced composites that would be two or three times as wide and weigh no more or even less than present equipment made of steel. Availability of such equipment would allow a farmer to process twice to three times the acreage within a given period of time. The equipment would be modular or foldable to allow passage over public roads.

With the trend towards one till or no till farming in the United States, there is a requirement for equipment that performs more than one operation at a time. Multifunctional equipment is weight constrained. In order to have the depth needed to place the various tools, the width of the equipment is reduced. Advanced composite components could allow wider equipment. With this sort of equipment a farmer could operate a larger farm without increasing labor requirements or use it to minimize the risk of operating a farm of given acreage. By being able to process more acreage in a given period of time, a farmer effectively increases the size of the temporal window constraining a given operation. For example if five days are available for seeding and a farmer can plant the seed in two days rather than four days, a rainstorm on the third day that washes away the seed planted on the previous two days has very different consequences. The farmer who can plant in two days can replace all the lost seed. The farmer who needs four days will be able to plant only half his acreage. Similar reasoning can be applied to harvesting of the crop. Availability of this type of equipment could have major impact on farm productivity.

The use of advanced composites in components for self-propelled equipment will follow rapidly their use in heavy duty trucks. The use of advanced composites in harvesting equipment is currently at the preliminary exploratory design stages and will not be in production for a decade. Many of the barriers to the production use of advanced composites in automobiles are also applicable here. Wear resistance is an additional important requirement in this instance since the equipment is to be exposed to much rougher service.

Scientific Instruments

The same properties that make graphite-epoxy composites valuable for components of satellites and space instrumentation systems are also used to advantage in earthbound scientific instruments. Extensive environmentally controlled facilities are often built to minimize temperatures, flexure and vibration induced errors when precision measurements are required and the use of graphite-epoxy composite structures could minimize the need for controlled environmental chambers. Examples of instruments constructed out of graphite-expoxy components include a tubular inside micrometer which has demonstrated an order of magnitude improvement over a standard metal version [68]. Optical benches made from graphite-epoxy composite are not only much lighter structures than standard benches that use heavy granite bases but they also do not require environmentally-controlled test chambers which are often more expensive than the instruments they house. Graphite-epoxy components are also finding applications in industrial diagnostic xray equipment in parallel with the use of graphite-epoxy composites in medical xray equipment [70].

Material Handling Equipment

The problems and opportunities for advanced composites in material handling equipment (such as bulldozers and forklift trucks) are similar to those encountered in agricultural equipment because the two classes of equipment are very much alike. Mobile cranes and aerial ladders are a special category of equipment in which advanced composites could be applied advantageously. In this instance weight reduction increases the mobility of the equipment and for example cranes with larger booms could be built without increasing the gross vehicle weight.

Other Potential Applications

The previous paragraphs list specific applications with advanced composites which were derived from interviews during the course of the study or which were referenced in the published literature that was reviewed. The list is not meant to be all inclusive and there are understandably other applications of advanced composites in existence which have not been mentioned. However it is believed that most of the major topics have been covered and it is also quite likely that applications of advanced composites will expand as the technology diffuses and costs are reduced. In principle any device currently made with fiberglass reinforced plastics could be made with a hybrid composite and the extent to which this will occur will depend on the associated costs and derived benefits.

The Economic Incentives

In estimating the economic incentive for some of the miscellaneous uses of graphite described above, straight-forward cost comparisons are appropriate. Consider the use of graphite in the production of picking sticks for textile machinery. In the absence of applicable regulations the textile manufacturer will use the graphite picking stick if, and only if, it is cost effective to do so. In determining whether or not this is true the operator would measure the cost of the graphite stick and the wood stick. This cost would be prorated over the usable lifetime of each stick. Further the value of the additional textile production possible because of the increased loom speed with the graphite picking stick would be determined. If the incremental cost associated with the graphite stick is outweighed by the longer life of the stick or the value of the increased textile production, the machine owner should select the graphite stick. If the costs of the wood stick and the graphite stick are comparable, the operator is likely to select the graphite stick because of the noise level reduction associated with the composite part. If OSHA or labor union regulations dictate noise levels below the current plant noise level, the graphite picking stick will be even more attractive. The actual value of this noise level reduction would depend on the stringency of the applicable regulations and the available alternatives to meeting the regulated noise levels. Similar cost comparisons including evaluation of incremental production made possible with composite parts are appropriate for many of the miscellaneous applications.

SECTION 5

U.S. PRODUCTION AND CONSUMPTION OF CARBON FIBER MATERIAL

U.S. SUPPLY OF CARBON FIBER

Since statistics on the production of carbon fiber are not reported, the only available figures are estimates based on surveys of the major producing companies. There are two primary surveys of this type. The first of these was developed by the Department of Commerce (DOC). This survey was based on existing studies of the demand for composites in aerospace, automotive and industrial applications and an extensive survey of fiber manufacturers, prepregers and final goods manufacturers in the sporting goods area. Preliminary results of the Department of Commerce (DOC) study were first presented at the NASA Langley Conference on Composite Materials in December 1979 and final results were published in the Carbon/Graphite Composite Material Study Second Annual Report 1979, [71] by the Office of Science and Technology.

The second major source of estimates on the U.S. production of carbon fiber is developed by Composite Market Reports, Inc. (CMR). These estimates are obtained through interviews and continued contact with composite industry personnel. Estimates are published in Annual Graphite Market Report [72].

Table 37 presents estimates of U.S. Capacity, Production, Imports, Exports and net supply from both the Department of Commerce and the Composite Market Reports, Inc. studies for 1976 through 1979. There is a reasonable difference between the two estimates, with the CMR estimates being more conservative, i.e., lower.

The Department of Commerce Study includes estimates for the following types of carbon fiber:

- Intermediate modulus (30-40 msi) high strength PAN- or pitch-based fiber
- High modulus (over 40 msi) and ultra-high modulus (over 70 msi) PAN-or pitch-based fiber
- Stablized (either oxidized only or oxidized and carbonized) PAN-or rayon-based fiber
- Low modulus (10-20 msi) PAN-or rayon-based fiber.

The Annual Graphite Market Report only includes the first three of these categories. The estimates presented here have been adjusted by CMR to account for the addition of this type of fiber. The following are estimates of annual totals for low-modulus carbon fibers:

1976	100,000 pounds (45,455 kg)
1977	100,000 pounds (45,455 kg)

TABLE 37 U.S. CARBON FIBER SUPPLY ESTIMATES, 1976 THROUGH 1979
1000 POUNDS (1000 KILOGRAMS)

	1976		1977		1978		1979	
	DOC*	CMR**	DOC	CMR	DOC	CMR	DOC	CMR
CAPACITY	841 (382)	700 (318)	860 (391)	830 (377)	933 (424)	900 (409)	1041 (473)	950 (432)
PRODUCTION	316 (144)	205 (93)	397 (180)	245 (111)	478 (217)	350 (159)	625 (284)	425 (193)
IMPORTS	143 (65)	150 (68)	192 (87)	195 (89)	291 (132)	255 (116)	440 (200)	355 (161)
EXPORTS	14 (6)	10 (5)	16 (7)	15 (7)	39 (18)	35 (16)	59 (27)	50 (23)
NET U.S. SUPPLY	445 (202)	345 (157)	573 (260)	425 (193)	730 (332)	570 (260)	1006 (457)	730 (332)

*SEE TABLE 6.2

**ESTIMATE BY COMPOSITE MARKET REPORTS, INC. BASED ON ANNUAL GRAPHITE MARKET REPORT, 1979

1978	110,000 pounds (50,000 kg)
1979	120,000 pounds (54,545 kg)

About 30 to 40 percent of this low-modulus carbon fiber is assumed to be used by the aerospace industry with the remainder being consumed by a variety of nonaerospace applications. Since these estimates were not obtained through the extensive surveying process used for the remainder of the production/supply factors, some inaccuracies may exist. These inaccuracies may be responsible for some of the discrepancies between the DOC and CMR results.

Projections of the U.S. supply/demand situation for the years 1980 through 1990 are based in part on the estimates of the existing capacity and production. Net U.S. supply will be a function of the demand for carbon-fiber-containing products. It is not likely that excess production or importation leading to the buildup of inventory levels would ever continue at a high rate or over a long period of time. At the same time the demand for each of the end use products will depend on the price of those products. This price is a function of the price of the inputs including the carbon fiber which is in turn a function of the producton cost and level of technology for producing the fiber. Thus projecting the supply and demand until 1990 involves making a complicated set of both explicit and implicit assumptions.

Early this year, Union Carbide announced that 15,000-filament PAN-based fiber imported from Toray was available at $18 per pound ($40 per kilogram). This price is competitive with that of the heavy tow fibers available from Hercules and Great Lakes Carbon. [73] This figure is down substantially (in constant dollars) from the 1972 price level. It is expected that the cost of producing the fiber will continue to decline due to technical improvements. The expectation of these price changes is either implicitly or explicitly included in the projections.

Table 38 contains projections of the U.S. supply and demand situtaiton from the DOC and CMR studies for 1980, 1983, 1985 and 1990. CMR is much more conservative than DOC in their estimate of supply; however, estimates of demand are similar in earlier CMR studies. CMR is somewhat less conservative in the long run. Note that CMR assumes the following annual totals for low-modulus carbon fiber:

1980	125,000 pounds (56,818 kilograms)
1983	140,000 pounds (63,636 kilograms)
1985	150,000 pounds (68,182 kilograms)
1990	175,000 pounds (79,545 kilograms)

U.S. CONSUMPTION OF CARBON FIBER CONTAINING GOODS

In order to estimate the carbon fiber disposal load to the solid waste stream, it is necessary to predict the volume of carbon fiber use by application. Previous sections have described some of the current and potential applications of graphite reinforced plastics and the economic incentives involved in each case. However, predicting the rate of market penetration for these applications and indeed the absolute sales volume is quite difficult.

Again, one of the important aspects of projecting future graphite material usage outside of the aerospace sector is the assumed fiber or prepreg cost. If future costs drop to a certain level, some applications become economical and are likely to go into

TABLE 38 U.S. CARBON FIBER SUPPLY AND DEMAND PROJECTIONS FOR 1980, 1983, 1985 AND 1990, 1000 POUNDS (1000 KILOGRAMS)

	1980		1983		1985		1990
	DOC*	CMR**	DOC	CMR	DOC	CMR	CMR
SUPPLY							
PRODUCTION	970*** (441)	510 (232)	4500*** (2045)	1700 (773)	11300*** (5136)	4300 (1955)	10000 (4545)
IMPORTS	690 (314)	440 (200)	1400 (636)	700 (318)	490 (223)	800 (364)	1000 (455)
EXPORTS	100 (45)	60 (27)	760 (345)	150 (68)	250 (114)	200 (91)	600 (273)
NET U.S. SUPPLY	1560 (710)	890 (405)	5140 (2336)	2250 (1023)	11540 (5245)	4900 (2228)	10400 (4727)
DEMAND							
AEROSPACE	470 (214)	400 (182)	1400 (636)	1300 (591)	2200 (1000)	2200 (1000)	5000 (2273)
SPORTING GOODS	260 (118)	310 (141)	350 (159)	500 (227)	360 (164)	700 (318)	1300 (591)
AUTOMOBILE	25 (11)	14 (6)	100 (45)	100 (45)	200 (91)	200 (91)	10000 (4545)
OTHER INDUSTRIAL	170 (77)	192 (87)	300 (136)	350 (159)	500 (227)	500 (227)	900 (409)
TOTALS	925 (420)	916 (416)	2150 (976)	2250 (1022)	3260 (1482)	3600 (1636)	17200 (7818)

*OFFICE OF SCIENCE AND TECHNOLOGY POLICY, EXECUTIVE OFFICE OF THE PRESIDENT, CARBON/GRAPHITE COMPOSITE MATERIAL STUDY, SECOND ANNUAL REPORT 1979, MARCH 15, 1980

**COMPOSITE MARKET REPORTS, INC.

***DEPARTMENT OF COMMERCE, PRESENTED AT NASA LANGLEY CONFERENCE ON ADVANCED COMPOSITE MATERIALS, DECEMBER 1979.

production within a few years. If price levels are assumed to be significantly lower, many more applications become cost effective. To illustrate this aspect of production dependency on material cost, two sets of estimates are provided. The first set assumes that graphite fiber or prepreg will drop to \$8 to \$10 per pound in 1985, and that by 1990 the average prices will be \$5 to \$6 per pound for prepreg or fiber, all based on 1979 dollars. The second set assumes that much higher fiber/prepreg production rates are achieved, so the prices might then drop to the \$5 to \$8 per pound level in 1985 and in the \$3 to \$5 per pound level in 1990, again based on 1979 dollars. The difference between \$5 per pound and \$10 per pound may seem small, but most experts agree that this might have a large effect on the number of components which may reach volume production. It is also assumed that the cost of fabricating the grapite parts averages \$3 to \$5 per pound in 1985 and drops to less than \$1 per pound in 1990 because of improved or more efficient manufacturing methods.

Table 39 presents CMR's estimated number of sales for carbon fiber containing units of a number of industrial, marine and sporting goods applications. In each estimate the current level of production and the overall market conditions have been considered. The two sets of estimates reflect different price levels assumed for carbon fiber as described above. Table 38 was actually derived from the figures in Table 39 and is a summary thereof.

TABLE 39 ESTIMATED CONSUMPTION OF GOODS CONTAINING CARBON FIBER BY APPLICATION, 1979 THROUGH 1990

	ESTIMATED NUMBER OF UNITS					
	SET #1			SET #2		
	1979	1985	1990	1979	1985	1990
I. INDUSTRIAL & MARINE						
A. AGRICULTURAL						
1. CULTIVATORS	-	-	2	-	2	25
2. SEEDERS	-	-	-	-	-	2
3. HARVESTERS	-	2	50	-	100	1,000
4. IRRIGATION SYSTEMS	-	-	10	-	10	100
5. WINDMILLS (WATER)	-	-	5	-	5	2,000
6. CROP DUSTERS (AIRCRAFT)	-	2	10	-	10	200
B. MATERIAL HANDLING & MINING						
1. EARTH MOVING	1	10	100	1	100	500
2. FORK LIFTS	-	10	100	-	100	1,000
3. AERIAL LADDERS	1	5	50	1	25	500
4. MOBILE CRANES	1	10	50	1	50	500
5. MINE SUPPORTS	1	100	1,000	1	500	5,000
6. CONVEYOR SYSTEMS	1	5	50	1	50	200
7. ELEVATORS & ESCALATORS	-	-	10	-	10	50
C. INDUSTRIAL MACHINERY						
1. TEXTILE MACHINES	50	100	200	50	200	1,000
2. PAPER & PRINTING	100	200	500	100	500	2,500
3. PLASTIC MANUFACTURING	10	50	100	10	100	300
4. FOOD PROCESSING	10	50	100	10	100	200
5. OFFICE MACHINES	30,000	150,000	300,000	30,000	250,000	500,000
6. BUSINESS MACHINES & COMPUTERS	15,000	200,000	500,000	15,000	200,000	500,000
7. MACHINE TOOLS	5	50	500	5	500	2,000
8. ROBOTICS	2	200	500	2	300	1,000
D. CHEMICAL & PETROLEUM						
1. STORAGE SYSTEMS	2	10	20	2	20	50
2. PIPING INSTALLATIONS	20	200	800	20	500	1,500
3. PUMPS & COMPRESSORS	1,000	5,000	10,000	1,000	7,500	15,000
4. VALVES	7,500	15,000	30,000	7,500	25,000	50,000
5. STRUCTURAL SUPPORT SYSTEMS	-	10	100	-	50	200
6. ENVIRONMENTAL CONTROL SYSTEMS	-	3	10	-	10	100
7. PROTECTIVE CLOTHING	500	25,000	50,000	500	50,000	100,000
8. PRESSURE VESSELS	20	500	1,000	20	1,000	5,000
E. MEDICAL						
1. X-RAY TABLES	300	1,000	2,000	300	1,000	2,000
2. CASSETTES	400	2,000	5,000	400	5,000	8,000
3. ARTIFICIAL LIMBS	50	500	5,000	50	4,000	10,000
4. WHEELCHAIRS	-	10	500	-	500	2,000
5. BRACES	50	400	4,000	50	2,000	6,000
6. WALKERS	1	2,000	10,000	1	5,000	25,000
7. IMPLANTS	50	250	500	50	300	700
8. SURGICAL INSTRUMENTS	100	500	3,000	100	2,500	5,000

TABLE 39 ESTIMATED CONSUMPTION OF GOODS CONTAINING CARBON FIBER BY APPLICATION, 1979 THROUGH 1990 (CONTINUED)

	ESTIMATED NUMBER OF UNITS					
	SET #1			SET #2		
	1979	1985	1990	1979	1985	1990
I. INDUSTRIAL & MARINE (CONTINUED)						
F. PHOTOGRAPHIC & SCIENTIFIC INSTRUMENTS						
1. OPTICAL PLATFORMS	10	50	500	10	100	1,000
2. CALIPERS & BENCHES	100	300	600	100	500	2,500
3. RECORDING INSTRUMENTS	-	80	200	-	100	1,000
4. TELESCOPES & BINOCULARS	-	500	5,000	-	1,000	10,000
5. MICROSCOPES	-	50	200	-	100	600
6. TRIPODS	10	100	1,000	10	1,000	5,000
7. CAMERAS (INCLUDING TV)	2	50	200	2	500	1,500
8. FILM PROCESSING EQUIPMENT	50	1,000	10,000	50	5,000	25,000
G. MUSICAL						
1. GUITARS & VIOLINS	300	500	1,000	300	700	1,500
2. OTHER INSTRUMENTS	5	25	100	5	40	200
3. TONE ARMS	500	5,000	10,000	500	8,000	20,000
4. SPEAKER CONES	50	15,000	60,000	50	50,000	100,000
5. CB ANTENNAS	15,000	30,000	50,000	15,000	50,000	75,000
6. COMMERCIAL ANTENNAS	-	10	100	-	20	150
H. CONSTRUCTION						
1. BRIDGES (INCLUDING MILITARY)	-	30	100	-	50	300
2. FENCING & SIGNING	-	50	500	-	200	1,000
3. REINFORCED CONCRETE PIPE	-	-	50	-	50	500
4. BUILDING CONSTRUCTION	-	-	100	-	50	200
5. LIGHTING POLES	-	100	1,000	-	500	2,000
I. ENERGY SOURCES						
1. SOLAR-THERMAL	-	2	50	-	50	500
2. SOLAR-ELECTRIC	-	5	50	-	10	100
3. WINDMILL (ENERGY)	-	200	10,000	-	500	20,000
4. HYDROELECTRIC	-	-	10	-	10	100
5. BATTERIES	20	5,000	50,000	20	10,000	100,000
6. NUCLEAR (CENTRIFUGE ROTORS)	-	5	10	-	10	200
7. INSULATION	100	500	1,000	100	1,000	5,000
J. MARINE						
1. MASTS & RIGGING	50	500	4,000	50	2,500	10,000
2. HULLS & KEELS	15	200	1,000	15	500	5,000
3. RUDDERS & TILLERS	50	500	2,000	50	1,000	10,000
4. DRIVE COMPONENTS	1	50	250	1	100	500
5. BUOYS	-	50	500	-	500	5,000
6. POLES	50	300	2,500	50	500	5,000
7. ENGINE COMPONENTS	-	1,000	4,000	-	3,000	10,000
8. BATTENS	1,000	5,000	10,000	1,000	7,500	15,000

TABLE 39 ESTIMATED CONSUMPTION OF GOODS CONTAINING CARBON FIBER BY APPLICATION, 1979 THROUGH 1990 (CONTINUED)

	ESTIMATED NUMBER OF UNITS					
	SET #1			SET #2		
	1979	1985	1990	1979	1985	1990
I. INDUSTRIAL & MARINE (CONTINUED)						
K. MISCELLANEOUS						
1. STANDARD BARS, SHEETS & PLATES	400	2,500	10,000	400	5,000	20,000
2. STANDARD TUBES & PIPE (SETS)	25	250	1,000	25	500	3,000
3. AIR TANKS	-	5,000	10,000	-	10,000	20,000
4. OTHER	500	50,000	150,000	500	100,000	300,000
II. SPORTS EQUIPMENT						
A. RACKET SPORTS						
1. TENNIS	150,000	250,000	350,000	150,000	300,000	400,000
2. RACQUETBALL	100,000	200,000	350,000	100,000	300,000	400,000
3. SQUASH & BADMINTON	5,000	10,000	15,000	5,000	15,000	20,000
4. TABLE TENNIS	100	5,000	20,000	100	10,000	30,000
B. FISHING RODS	850,000	1,300,000	1,900,000	850,000	1,600,000	2,300,000
C. GOLF SHAFTS (80% SHIPPED OVERSEAS)	240,000	350,000	400,000	150,000	300,000	400,000
D. SKI EQUIPMENT						
1 SNOW SKIS	500	20,000	50,000	500	35,000	50,000
2. WATER SKIS	1,000	2,000	3,000	1,000	2,500	4,000
3. SKI POLES	10,000	100,000	250,000	10,000	150,000	300,000
E. OTHER						
1. ARROWS	150,000	400,000	800,000	150,000	700,000	1,500,000
2. BICYCLE FRAMES	50	500	1,000	50	3,000	5,000
3. HOCKEY STICKS	200	1,000	5,000	200	5,000	10,000
4. CANOES & KAYAKS	100	300	800	100	1,000	3,000
5. SNOWMOBILES	25	500	4,000	25	4,000	10,000
F. ALL OTHER SPORTING GOODS	-	50,000	200,000	-	150,000	400,000

SOURCE: COMPOSITE MARKET REPORTS, INC.

SECTION 6

DISPOSAL OF GRAPHITE PRODUCTS

THE MUNICIPAL SOLID WASTE STREAM

Various amounts of carbon fiber and graphite reinforced plastics are disposed of throughout the production/consumption cycle. The length of this cycle and the flow of refuse during the cycle will vary depending on the particular graphite product, the form of composite used and the production process involved, as well as the expected product life. For instance a CB antenna might last only a few years while an agricultural irrigation system might have a much longer life. Further, a tennis racket manufacturing firm which cuts racket blanks from sheets of prepreg will experience a much higher scrappage rate than one that inlays carbon fiber in a wooden racket.

The production of graphite products generally requires several steps either within a single company or among a number of companies. The major steps are fiber production, prepreg manufacture and final good production. During each of these phases a certain amount of refuse is accumulated through production scrappage.

The scrappage rate and disposal procedures of 17 sports good manufacturers were determined (Table 40). It was assumed that the practices of these manufacturers reflect those of consumer good manufacturers in general. It was found that sports equipment manufacturers are not overly concerned about their carbon fiber scrap disposal, and what little they have is put into their regular waste container for municipal pickups (one exception to this is Fansteel/FRRP which stores its scrap in a 300 lb. polyethylene container and has never disposed of it yet). Most of them have very little scrap (in the 1 to 5 percent range), and attempt to minimize this further (to less than 1 percent) by turning it into small marketable items such as golf club inserts (Grafalloy Corporation). A few even claim not to have any scrap at all due to the fact that they make their prepregs to kit. A good number of the production managers are aware of the potential hazard in burning graphite-fiber, and some state that a warning against incineration as well as electrical conductivity and possible skin irritation is clearly marked on the graphite package. However, none have ever received any special instructions on scrap disposal from their supplier.

It is thus concluded that both the fabrication scrap and the carbon fiber actually used in the manufacture of consumer goods is eventually disposed into the municipal waste stream. Thus sports equipment and musical applications eventually find their way into the municipal solid waste stream. In addition certain types of photographic and scientific equipment are primarily consumer goods; these would include the following:

TABLE 40 INDUSTRY DISPOSAL PROCEDURES--SPORTING GOODS MANUFACTURERS

COMPANY	PRODUCT	AMOUNT OF SCRAP (LB/YR)	SPECIAL CONTAINER?	DISPOSAL METHOD	AWARE OF PROBLEM?	SPECIAL INSTRUCTIONS?
ALDILA, INC.	GOLF SHAFTS TENNIS AND RACKETBALL RACKETS	250	NO	BURIED	YES	NO
AMERICAN SPORTS EQUIPMENT CO.	TENNIS RACKETS	0	N/A	N/A	YES	NO
AMF HEAD DIVISION	TENNIS RACKETS	< 50	NO	BURIED	YES	NO
BROWNING MFG. CO.	FISHING RODS	≈25	NO	NOT KNOWN	NO	NO
COMPOSITE DEVELOPMENT CORP.	FISHING RODS	≈25	NO	UNWILLING TO DISCUSS	YES	?
FAUSTEEL/FRRP	RECREATION PRODUCTS	UNWILLING TO SAY	YES 300 LB POLYETHYLENE CONTAINER	KEPT ON SITE--NEVER YET DISPOSED	YES	NO
FENWICK-WOODSTREAM	FISHING RODS	≈200	NO	BURIED	NO	NO
GORDON PLASTICS INC.	ARROW SHAFTS	UNWILLING TO DISCUSS				
GRAFALLOY CORP.	GOLF SHAFTS & TENNIS RACKETS	< 300	NO	NOT KNOWN	NO	NO
GRAPHITE MASTER, INC.	SPORTS EQUIPMENT	0	N/A	N/A	YES	NO
GRAPHITE SALES CO.	TENNIS RACKETS	0	N/A	N/A	YES	NO
LAKE KING ROD CO.	UNWILLING TO DISCUSS					
LAMIGLAS INC.	GRAPHITE ARROWS	< 250	NO	NOT KNOWN	NO	NO
ORVIS COMPANY, INC.	FISHING RODS	< 200	NO	BURIED	YES	NO
RESEARCH ENG. CORP.	FISHING RODS	< 50	YES FREEZER	KEPT LOOKING FOR BUYER	YES	NO
SKYLINE INDUSTRIES INC.	UNWILLING TO DISCUSS					
STARWIN INDUSTRIES	TENNIS RACKETS	< 50	NO	BURIED	YES	NO

- Recording instruments
- Telescopes and binoculars
- Tripods
- Cameras.

The municipal solid waste stream is composed of refuse from residential, commercial and institutional sources; however, large consumer products such as automobiles generally enter the industrial solid waste stream. Needless to say there is some overlap between consumer and industrial products and, therefore, municipal waste cannot be absolutely uniquely defined.

On average each of the photographic, scientific and musical products bought by consumers will contain 0.15 pounds (.068 kilograms) of carbon fiber. [74] All of the carbon fiber and graphite products will at some point be disposed. Therefore the 1980 consumer demand will enter the post-1980 municipal solid waste stream. Using CMR's projections, the potential consumer disposal of carbon fiber into the municipal waste stream has been determined. These estimates are presented in Table 41.

TABLE 41 ESTIMATE OF POTENTIAL CONSUMER DISPOSAL OF CARBON FIBER INTO MUNICIPAL WASTE STREAM

APPLICATION	AMOUNT DISPOSED, [1000 LB (1000 KG)]					
	1980		1985		1990	
SPORTING GOODS	310.0	(140.6)	700.0	(317.5)	1,300.0	(589.7)
MUSICAL INSTRUMENTS	2.4	(1.1)	7.5	(3.4)	18.2	(8.3)
PHOTOGRAPHIC AND SCIENTIFIC	-	(-)	1.0	(.5)	1.0	(.5)
TOTAL	312.4	(141.7)	708.5	(321.4)	1,319.2	(598.5)

Figure 10 presents a detailed flow of material in the municipal waste stream. It can be seen that there are a number of options for handling refuse in this waste stream, including source separation, landfill and incineration. As indicated by Figure 10 open dumps are not an acceptable method for disposal of municipal solid waste and are thus crossed out in the figure.

Currently the disposition of municipal waste is as follows:

- 89 percent landfill
- 4 percent incinerated without recovery
- 1 percent incinerated for energy recovery
- 6 percent source separation. [75]

There are a number of pressures for changing this mix in the future including increases in energy costs, shortages in land available for landfill, environmental concerns, etc. These pressures as well as alternative future scenarios are discussed in Section 8.

The potential danger of incinerating carbon fiber material comes from the emission of airborne particulates shown at the bottom of the diagram. The technical properties of municipal incineration processes that affect the amount of carbon fiber emitted are discussed in Section 7.

THE INDUSTRIAL SOLID WASTE STREAM

Industrial scrappage, used industrial products and oversized consumer products will enter the industrial waste stream. The quantity of fiber consumed (and thus disposed of) through industrial products is much larger than that used in consumer goods. Further, the relative importance of industrial use is expected to increase over the next ten years or more. This growth is most likely because the sporting goods and other consumer product markets will probably stabilize while a longer growth period and an increase in the number of applications is expected in the industrial area. Figure 11 depicts the increasing importance of the industrial disposal load. For every 1.1 kilograms of carbon fiber produced in 1980, 0.1 kilograms will be fabrication scrap and thus enter the industrial waste stream immediately, while 0.7 kilograms will be used in industrial products. Thus about 73 percent of the fiber produced will eventually enter the industrial solid waste stream. In the same manner about 91 percent of the carbon fiber produced in 1990 will eventually enter the industrial refuse system.

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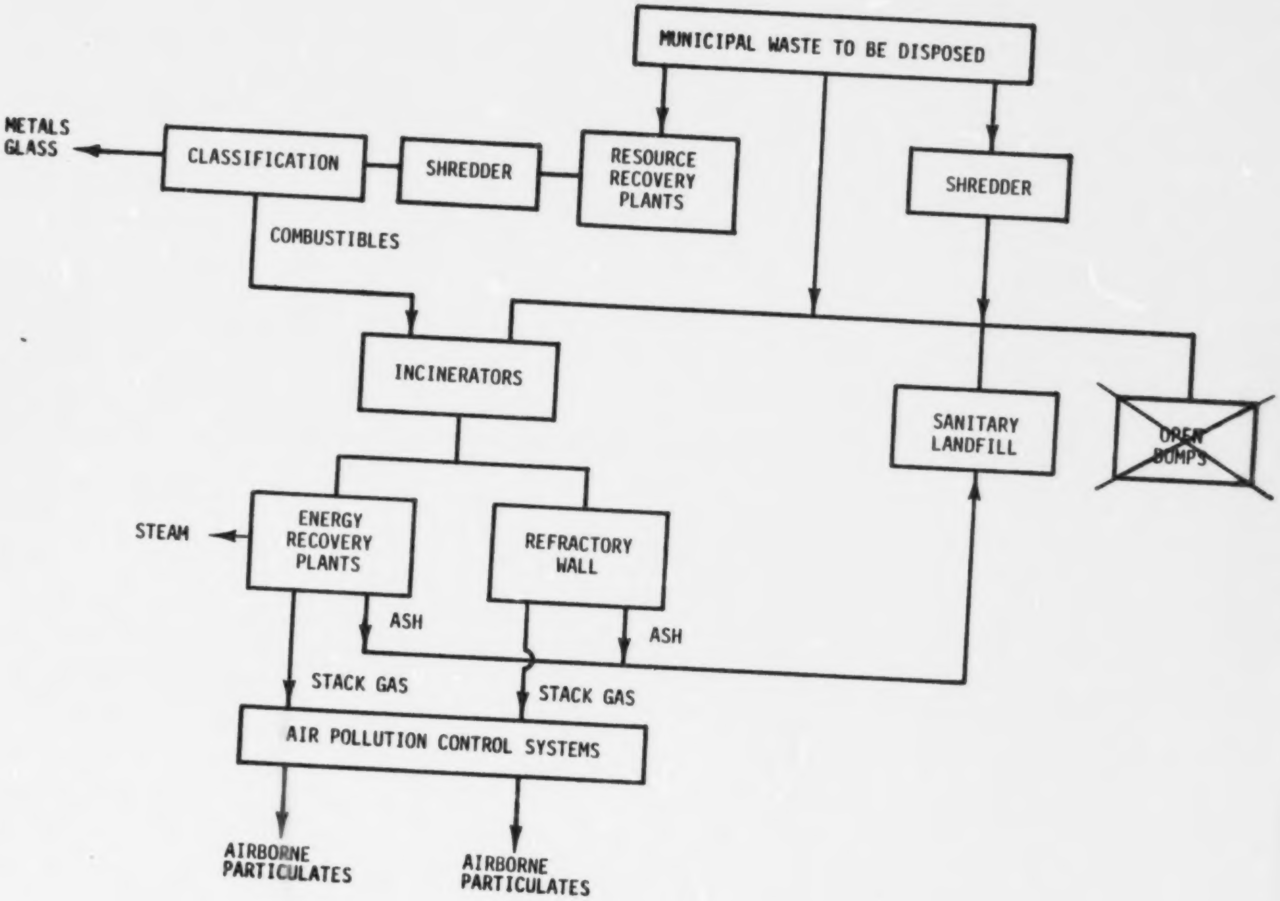

FIGURE 10 MATERIAL FLOWS IN THE PROCESSING OF MUNICIPAL WASTE

1980 TOTAL CONSUMPTION
430,913 KG (950,000 LBS)*

1990 TOTAL CONSUMPTION
6,894,604 KG (15,200,000 LBS)*

*PROJECTIONS BY MARTIN BURG.

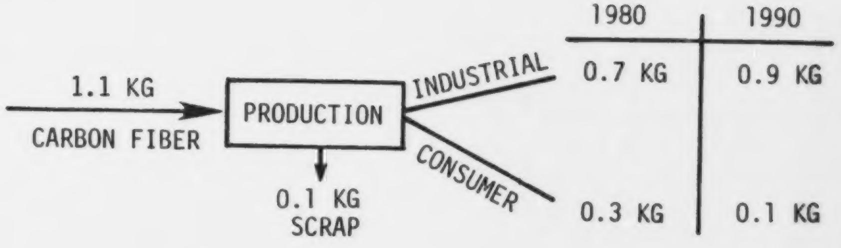

FIGURE 11 PROJECTED CONSUMPTION OF CARBON FIBER BY INDUSTRY AND CONSUMERS IN 1980 AND 1990

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Since little is known about industrial disposal practices, a preliminary study was conducted to determine how scrap and industrial prototypes are disposed. All of the manufacturers of fiber and prepreg as well as 18 aerospace firms, nine other industrial firms and five U.S. government agencies were contacted and interviewed as to their graphite-fiber scrap disposal procedures as well as their general awareness of potential problems associated with its disposal. Summaries of the responses obtained are shown in Tables 42 through 45, for manufacturers of fiber and prepreg, aerospace firms, other industrial firms and government agencies respectively.

The manufacturers of fiber and prepreg tend to recycle, reuse or otherwise limit the amount of scrap produced. Many recycle the carbon fiber scrap by chopping it up while prepregs with thermoplastic resins are simply melted down and reused. When disposal is necessary, some type of container is used to segregate the fiber from other industrial wastes and landfill is generally the procedure followed. Most companies are conscientious in advising their customer about handling carbon fiber material. Some attach labels stating acceptable disposal procedures while others recommend recycling. Stackpole would be inclined to incinerate the scrap if the cost of fiber fell below $10 per pound.

In general the aerospace firms are knowledgeable about the properties of carbon fiber and composites. Most scrap is segregated and landfilled. However many firms generate a substantial amount of scrap (as high as 50%, see Table 43) but have not instituted recycling programs. Some companies cure their scrap into blocks while others put the scrap into 55 gallon drums.* Another area of concern at a few plants is the danger of carbon fiber composite dust and its effect on their employees' health. To protect their employees, dust collectors have been installed. The aerospace industry thus seems to take appropriate precaution when disposing of carbon fiber scrap.

The third category consists of other industrial users. Many of these companies are in the research and development stage and use very little carbon fiber. The amount of scrap is insignificant and special disposal procedures are not used. Companies that are in the production stage generally landfill the scrap. Graftek expressed interest in future incineration, but is presently using landfill.

The amounts of graphite fiber used by the U.S. government agencies (Table 45) are minimal, as they too are involved in the research and development phase of products. Nevertheless they all separate graphite fiber from their combustible scrap and store it for landfill burial.

After many phone conversations a pattern of responses became evident. Due to the high cost of fiber, initially efficiency in production is stressed. However the major users of carbon fiber are not as thrifty; in particular, the aerospace group is a good example. This can be ascribed to the facts that the aerospace industry is less competitive than most and that fiber makes up only a very small part of the total cost of their products. They can thus afford to waste carbon fiber. In other emerging industries scrap may affect profits more significantly as it does with the manufacturers of prepreg and fiber. In summary the amount of carbon fiber scrap seems to be minimal among manufacturers and users, except within the aerospace industry. While

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*Used parts are stored on site while awaiting disposal by landfill.

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TABLE 42 INDUSTRY DISPOSAL PROCEDURES--MANUFACTURERS OF FIBER AND PREPREG

COMPANY	DISPOSAL	SPECIAL CONTAINER	PERCENT SCRAP	FUTURE PLANS	REMARKS
AVCO	LANDFILL	YES	10%	NO	--
CELANESE	LANDFILL	YES	MINIMAL	--	--
GR. LAKES RES.	LANDFILL	YES	SMALL	NO	HAD ACCIDENT IN EARLY 70S
HAVES-REINHOLD	RECYCLE	--	NONE	--	COST OF FIBER FELL FROM $600-$20/LB
HERCULES	LANDFILL	YES	1%	RECYCLE	--
HITCO	RECYCLE	--	NONE	--	--
L&T	RECYCLE	--	NONE	--	ADVISE RECYCLING TO CUSTOMERS
STACKPOLE	WAREHOUSE	YES	UNKNOWN	INCINERATION	RECYCLES
UNION CARBIDE	LANDFILL	YES	UNKNOWN	--	ADVISES LANDFILL

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TABLE 43 INDUSTRY DISPOSAL PROCEDURES--AEROSPACE INDUSTRIES

COMPANY	DISPOSAL	SPECIAL CONTAINER	PERCENT SCRAP	FUTURE PLANS	REMARKS
BELL HELICOPTER	LANDFILL	YES	30%	RECYCLING	R&D STAGE
BENDIX CORP	LANDFILL	YES	SMALL	--	C-C COMPOSITES
BOEING/W	LANDFILL	YES	50%	NONE	--
DOUGLAS AIRCRAFT	LANDFILL	YES	15%	--	DUST COLLECTORS
FAIRCHILD	LANDFILL	YES	SMALL	--	--
GENERAL DYNAMICS	LANDFILL	YES	30%	NONE	AWARE OF EPA STUDY ON DISPOSAL
KAMAN CORP	LANDFILL	NO	3-5%	--	R&D STAGE
LOCKHEED	LANDFILL	YES	10%	NONE	--
MCDONALD DOUGLAS	LANDFILL	YES	33%	NONE	--
NORTHROP	LANDFILL	NO	25%	RECYCLING	--
ROCKWELL	LANDFILL	YES	5%	NONE	--
SIKORSKY	LANDFILL	YES	15%	NONE	--
S.C.I.	LANDFILL	YES	10%	NO	SMALL USER AT PRESENT
TELEDYNE RYAN	LANDFILL	YES	30%	NONE	CONCERNED ABOUT HEALTH EFFECTS
THIOKOL	LANDFILL	NO	5%	RECYCLING	--
TRW	--	YES	SMALL	--	--
GRUMMAN	LANDFILL	YES	25-40%	NONE	CURE SCRAP INTO A BLOCK
VOUGHT	LANDFILL	YES	25%	UNKNOWN	BOEING 757--INCREASE IN USE EXPECTED

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TABLE 44 INDUSTRY DISPOSAL PROCEDURES--OTHER INDUSTRIAL

COMPANY	DISPOSAL	SPECIAL CONTAINER	PERCENT SCRAP	FUTURE PLANS	REMARKS
BABCOCK & WILCOX	LANDFILL	YES	10%	--	PRODUCE BALL VALVES
BUDD CO.	UNKNOWN	NO	UNKNOWN	--	--
CATERPILLAR TRACTOR	UNKNOWN	UNKNOWN	UNKNOWN	UNKNOWN	R&D STAGE
FORD MOTOR CO.	UNKNOWN	NO	MINIMAL	--	--
GMC TRUCK & COACH	--	YES	SMALL	--	NOT IN PRODUCTION
GRAFTECK	LANDFILL	NO	3%	INCINERATION	--
INTERNATIONAL HARVESTER	--	NO	2%	--	R&D STAGE
INTERNATIONAL PAPER	LANDFILL	YES	10%	DESTROY FIBER CHEMICALLY	--

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TABLE 45 INDUSTRY DISPOSAL PROCEDURES--U.S. GOVERNMENT AGENCIES

AGENCY	AMOUNT OF SCRAP (LBS/YR)	SPECIAL CONTAINERS?	DISPOSAL METHOD
AIR FORCE FLIGHT DYNAMICS LABORATORY	< 10	NO	BURIED
AIR FORCE MATERIALS LABORATORY	< 5	YES (WITH ALL CHEMICAL LAB TRASH)	BURIED
ARMY MATERIALS & MECHANICS RESEARCH CENTER	< 5	YES (SPECIAL BUCKET FOR ALL RESIN MATERIALS)	BURIED
NASA--LANGLEY RESEARCH CENTER	< 10	YES (IN AIR-FILTERED ROOM)	BURIED
NAVAL SURFACE WEAPONS CENTER	< 40	NO	BURIED

the aerospace industry disposes of the waste properly by landfill, other methods to utilize the waste should be examined. Recycling or reusing some of the waste could eliminate a significant amount of waste being landfilled. If these are not economically feasible, alternative methods of disposal could be developed.

SECTION 7

TECHNICAL AND ECONOMIC ASPECTS OF INCINERATION

DESCRIPTION OF INCINERATORS

The principal function of an incinerator is to transform refuse into gases and ash, which is a sterile residue of significantly lower weight and volume. The energy released by incineration of refuse is a byproduct which may be recovered in the form of high pressure steam. While common in Europe, the recovery of energy from waste incinerators was not common practice in the United States prior to the energy crisis. Steam recovery from combustion of refuse, or refuse and coal, is now being implemented in various parts of this country.

A typical mixed domestic and commercial refuse is presented in Table 46 by category and component. Because the composition and moisture content of refuse varies significantly with season, region and weather conditions, the characteristics of a specific lot of refuse may differ significantly from those listed in Table 46. While nominally not significantly different from peat in heating value, refuse differs significantly from fossil fuels in terms of variability and ease of handling.

TABLE 46 TYPICAL REFUSE COMPOSITION

CATEGORY	WEIGHT PERCENT (AS PRED.)	COMPONENT	WEIGHT PERCENT
METAL	8.7	MOISTURE (H_2O)	28.16
PAPER	44.2	CARBON (C)	25.62
PLASTICS	1.2	OXYGEN (O)	21.21
LEATHER AND RUBBER	1.7	HYDROGEN (H)	3.45
TEXTILES	2.3	SULFUR (S)	0.10
WOOD	2.5	NITROGEN (N)	0.64
FOOD WASTE	16.6	ASH	20.82
YARD WASTE	12.6		
GLASS	8.5		
MISCELLANEOUS	1.7		

SOURCE: D.G. WILSON, EDITOR, "THE TREATMENT AND MANAGEMENT OF URBAN SOLID WASTE," CHAPTER 7, "MUNICIPAL INCINERATION," TECHNOMIC PUBLISHING CO., INC., WESTPORT, CN 06880, 1972.

Design and Operation of Municipal Mass-Fired Incinerators

The basic operational components of a mass-fired incinerator are outlined in Figure 12. As indicated in this figure the incinerator requires a refuse loading area, a storage bin, a refuse feed system, a combustion chamber, an air supply, residue quench and residue disposal system, flue gas cooling system and flue gas and water treatment systems. The flue gases may typically contain about 22 pounds (10 kg) of particulates per metric ton of refuse and must be cleaned before dispersal into the atmosphere in order to meet environmental standards. Most incinerators currently use dry electrostatic precipitators to reduce the fly ash concentrations to acceptable levels. This requires that the gases be cooled to temperatures of approximately 400° F to 700° F that are tolerated by electrostatic precipitators.

The stoichiometric relations and adiabatic flame temperatures for the combustion of typical refuse such as in Table 46, are presented in Table 47 for various amounts of air. If refuse could be burned with the minimum amount of air required to obtain complete combustion (zero percent excess air), for every ton of refuse burned, over three tons of air would be required and about four tons of flue gas at initial temperatures close to 3000°F would have to be processed by the gas quench and air pollution control systems before discharge into the atmostphere. Because of difficulties in metering air to the fuel at the desired locations, and because of corrosion problems with the furnace materials, typical mass-fired incinerators operate with significant levels of excess air which moderates the temperatures encountered in the combustion chamber. Conventional refractory walled furnaces operate below the fusion temperature of ash, with typical minimum flue gas temperatures of the order of 1800° F to 2000° F to prevent damage to the refractory from molten fly ash. Minimum temperatures of 1400° F or even 1600° F are required to prevent the escape of malodorous, noxious gases. These constraints on temperature indicate that the range of excess air for a conventional refractory lined furnace could be from 100 to 250 percent.

Modern incinerators which have water tube walls lining the combustion chamber, and which recover heat directly from the combustion zone, can operate with significantly less excess air than a conventional refractory wall incinerator. With this approach, energy is recovered in the form of steam generated in the water tube walls and the quantity of flue gas generated is significantly reduced, reducing the size of the downstream equipment required. Excess air requirements are reduced to about 40 to 60 percent in this case. Figure 13 is a representation of the Chicago Northwest Steam Generating Incinerator which became operational in 1971 and which is representative of this class of incinerator.

In modern incinerators refuse is fed continuously on a traveling or oscillating grate where it comes into contact with air and is burned. The combustion of refuse is a complex process which entails drying, pyrolysis, ignition, char formation, gasification, oxidation and finally burnout as outlined in Figure 14. Typically residence times on the grate of 40 to 60 minutes are required, with higher values needed when burning either bulky objects or refuse with a higher moisture content. In order to achieve efficient combustion, air is introduced both from below the grate and above the grate. The amount of air introduced below the grate establishes, to a significant extent, the size and amount of particulate material elutriated from the combustion bed [76]. For a typical refuse burning rate of 68 lbs./hr.-ft^2 of grate area [77], as shown in Table 48, gas velocity through the bed is of the order of three meters/second. This gas velocity is sufficient to blow out of the combustion bed carbon particles formed by the

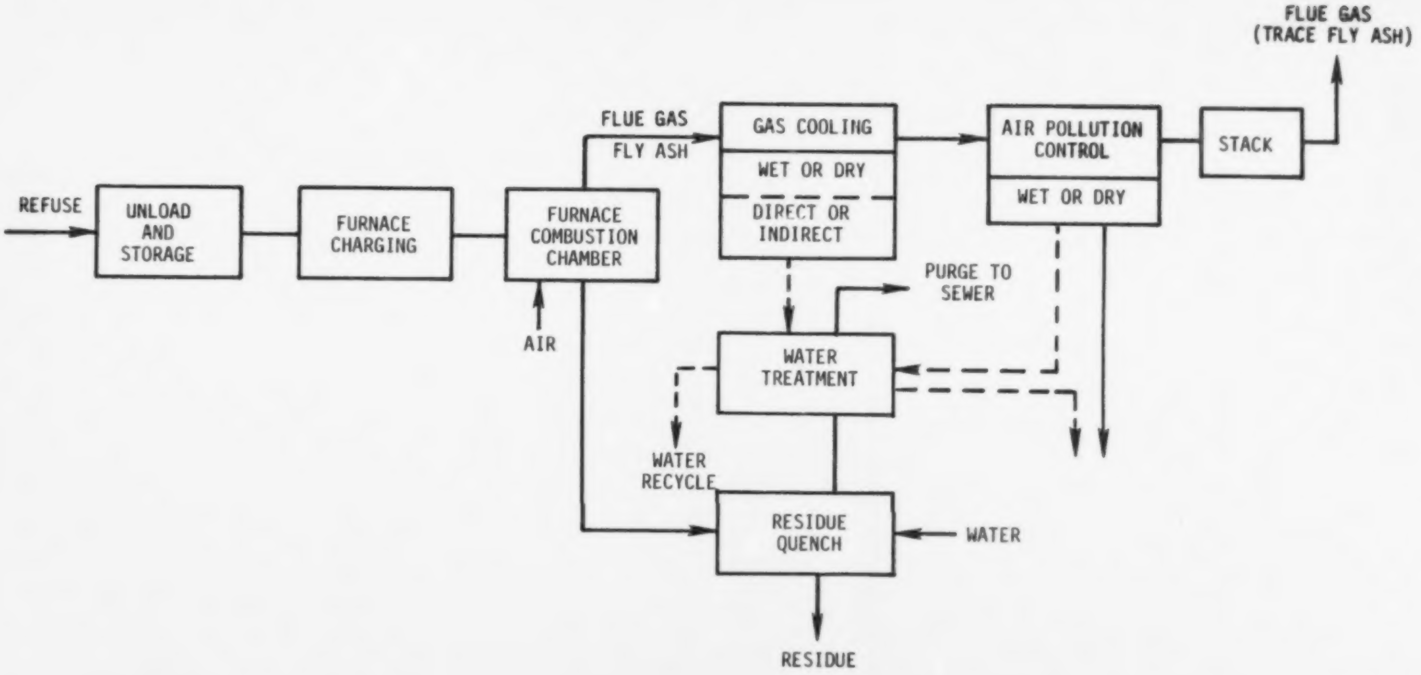

FIGURE 12 OPERATIONAL FLOW DIAGRAM FOR AN INCINERATOR

TABLE 47 STOICHIOMETRIC RELATIONS AND ADIABATIC FLAME TEMPERATURES FOR THE COMBUSTION OF A TYPICAL REFUSE WITH VARYING AMOUNTS OF EXCESS AIR*

PERCENT EXCESS AIR	0%	50%	100%	200%	300%
AIR REQUIREMENTS (LBM AIR PER LBM REFUSE)	3.21	4.81	6.42	9.63	12.84
FLUE GAS GENERATION (LBM FLUE GAS PER LBM REFUSE)	4.03	5.64	7.25	10.45	13.65
ADIABATIC FLAME TEMPERATURE (F)	3,020.00	2,450.00	1,990.00	1,460.00	1,180.00
DEW POINT (F)	147.00	135.00	126.00	113.00	104.00

*BASED ON APPROXIMATELY 2,750 CALORIES/GRAM GROSS HEATING VALUE (4,950 BTU/LB)

SOURCE: D.G. WILSON, EDITOR, "THE TREATMENT AND MANAGEMENT OF URBAN SOLID WASTE," CHAPTER 7, "MUNICIPAL INCINERATION," TECHNOMIC PUBLISHING CO., INC., WESTPORT, CN 06880, 1972.

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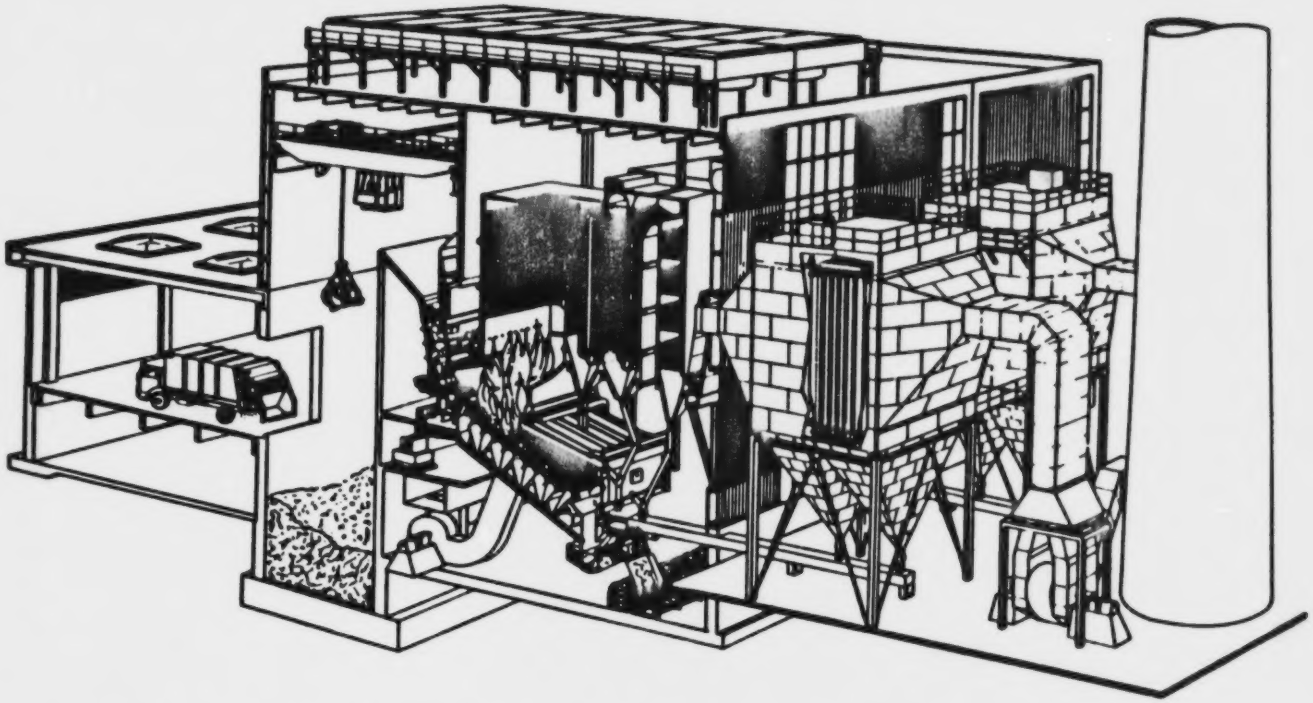
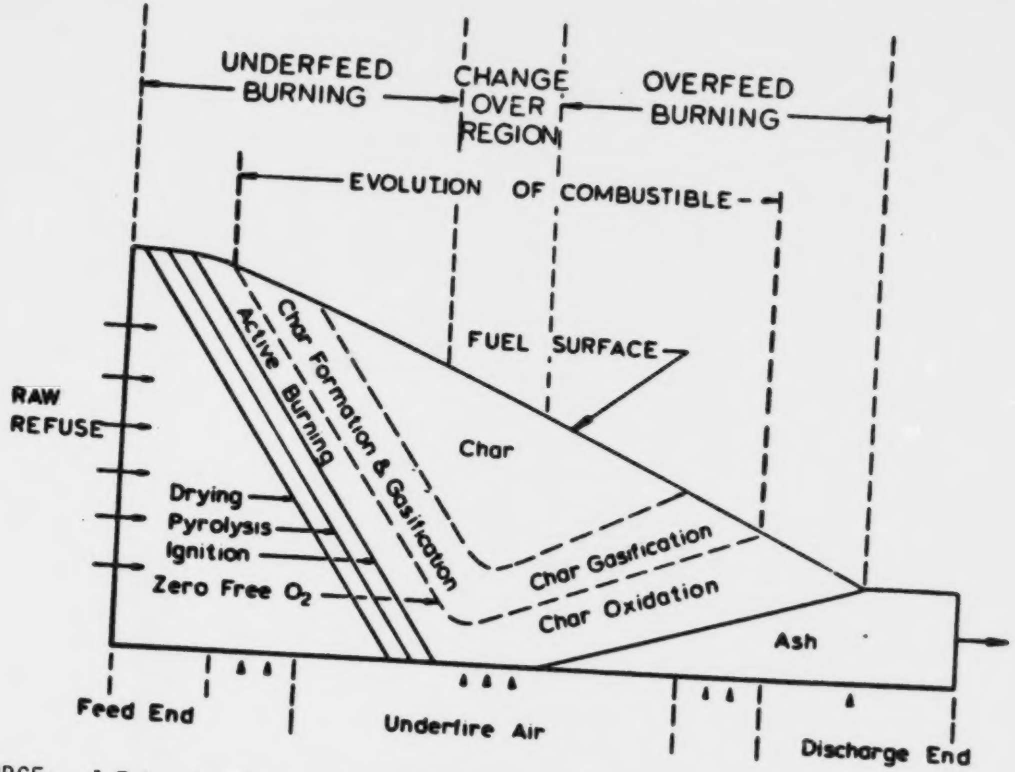


SOURCE: G. STABENOW, "THE CHICAGO NORTHWEST AND HARRISBURG INCINERATORS: A PROVEN METHOD OF ENERGY RECOVERY AND RECYCLING OF FERROUS METALS," PROCEEDINGS OF THE 1976 NATIONAL WASTE PROCESSING CONFERENCE, ASME, NEW YORK, NY, 1976, P. 81.

FIGURE 13 CHICAGO NORTHWEST INCINERATOR



SOURCE: J.E.L. ROGERS, A.F. SAROFIM AND J.B. HOWARD, PROCEEDINGS OF THE 1972 NATIONAL INCINERATOR CONFERENCE, ASME, NEW YORK, NY, 1972, P. 135.

FIGURE 14 SIMPLIFIED SCHEMATIC OF PROCESSES OCCURING IN THE FUEL BED ON A TRAVELING GRATE

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TABLE 48 CALCULATED SIZE OF CARBON PARTICLES FLUIDIZED BY UNDER FIRE AIR

UNDER FIRE AIR AS PERCENT EXCESS AIR	0	50	100
REFUSE BURNING RATE, LBS/HR-FT^2	68	68	68
GAS FLOW, LBS/HR-FT^2	274	383	492
ESTIMATED GAS VELOCITY, M/SEC	2.6	3.1	3.3
CRITICAL FLUIDIZATION DIAMETER FOR CARBON SPHERE, μm	310	330	350

charring of refuse, or as unburned carbon fiber from carbon fiber reinforced composites, with an equivalent spherical diameter of 300μm to 350μm. With these gas velocities, it is estimated that the particles elutriated from the burning bed remain in the combustion zone, where they see peak temperatures for only a few seconds (i.e., less than four seconds). This is insufficient time to result in the combustion of particles of such size, so that they are carried along with the flue gases. Without the use of appropriate air pollution control equipment, these particles would escape into the atmosphere.

Particulate Control

Niessen and Sarofin [76] examined and analyzed data on particulate furnace emissions from 50 different incinerators prior to treatment of the flue gases by air pollution control equipment. Their results indicate wide day-to-day variations in the levels of emissions for any given incinerator which tend to mask variations in particulate emissions from one incinerator to another. A correlative factor was the under fire air rate. The design specifics of any given incinerator had less influence on the variability of emissions than the daily variation in the properties of the refuse being burned and the method of operation chosen. This is well exemplified by the data presented in Table 49 which were obtained by Walker and Schmitz [78]. Walker and Schmitz examined the level and size distribution of particulate emissions from three different types of mechanically stoked municipal incinerators. While some differences in the level of particulate emissions were noted between the three furnaces, the variations in emission levels for any given furnace were of the same magnitude as the differences between furnaces. The emission levels were also approximately two orders of magnitude greater than the federal standard of 0.18 gr/NM^3 which is equivalent to 0.005 gr/SCF. Walker and Schmitz also obtained data on the size distribution of the particles leaving the three furnaces. These data are presented in Figure 15. Since the particle removal efficiency of all dust arresting equipment used for air pollution control in industry decreases with decreasing particle size, the implication of Figure 15 is that in order to meet federal emissions standards, essentially all particles

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TABLE 49 CHARACTERISTICS OF FURNACE EMISSIONS OF THREE CONTINUOUS FEED INCINERATORS

INCINERATOR	1	2	3
CAPACITY TONS/24 HR. DAY	250	250	120
SYSTEM DESCRIPTION GRATE	MULTIPLE TRAVELING	RECIPROCATING	ROCKING
AIR FEED	OVERFIRE & AIR WALL COOLING	UNDERFIRE ONLY	OVERFIRE AND UNDERFIRE
REFUSE CHARGED, (TONS/HR.)			
AVERAGE	12.9	9.8	5.1
MINIMUM	10.3	8.0	5.0
MAXIMUM	15.8	11.0	5.3
FURNACE OUTLET TEMPERATURE, F			
AVERAGE	1469	1211	1593
MINIMUM	1320	975	1509
MAXIMUM	1673	1360	1714
UNDER FIRE AIR, SCFM/FT^2 OF GRATE			
AVERAGE	41.8	105	17.5
MINIMUM	32.6	89	11.1
MAXIMUM	68.7	130	21.9
FLUE GAS VOLUME, (10^3 ACFM)			
AVERAGE	143	142	65
MINIMUM	127	127	60
MAXIMUM	170	158	72
PARTICLE EMISSIONS, GR/SCF			
AVERAGE	0.553	0.694	0.380
MINIMUM	0.435	0.539	0.258
MAXIMUM	0.743	0.820	0.540
PARTICLE EMISSIONS, LBS./TON REFUSE			
AVERAGE	12.4	25.1	9.1
MINIMUM	7.7	17.3	6.1
MAXIMUM	18.9	36.6	11.0

SOURCE: A.B. WALKER AND F.W. SCHMITZ, "CHARACTERISTICS OF FURNACE EMISSIONS FROM LARGE MECHANICALLY STOKED MUNICIPAL INCINERATORS", PROCEEDINGS OF THE 1966 NATIONAL INCINERATOR CONFERENCE, ASME, NEW YORK, NY, 1966, P. 64.

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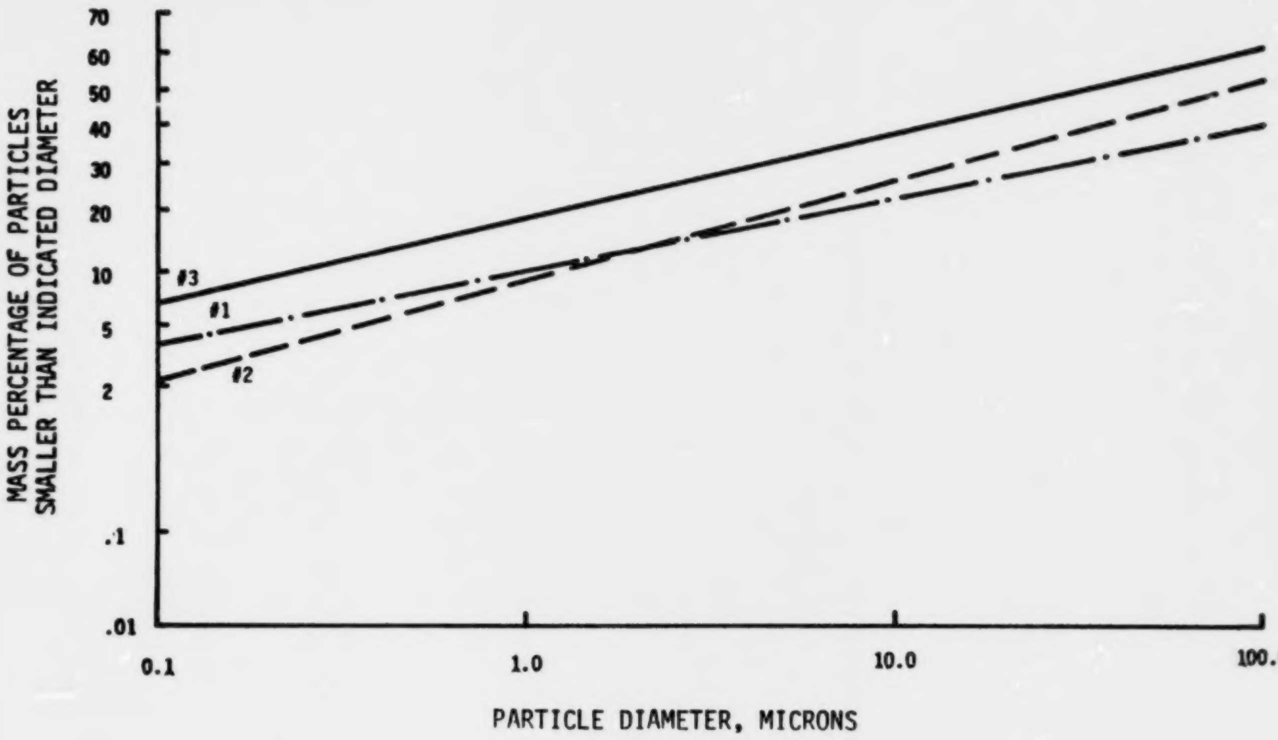

SOURCE: A.B. WALKER AND F.W. SCHMITZ, "CHARACTERISTICS OF FURNACE EMISSIONS FROM LARGE MECHANICALLY STOKED MUNICIPAL INCINERATORS", PROCEEDINGS OF THE 1966 NATIONAL INCINERATOR CONFERENCE, ASME, NEW YORK, NY, 1966, P. 64.

FIGURE 15 PARTICLE-SIZE DISTRIBUTIONS OF FURNACE EFFLUENTS

larger than 1 μm-3 μm must be removed from the flue gases before they leave the incineration system.

The collection efficiency of various types of commonly used, dust arresting equipment in industry as a function of particle size are summarized in Table 50. Electrostatic precipitators, dry or irrigated, venturi scrubbers and bag filters appear to be the only forms of commercially available equipment listed in Table 50 that have the capability to meet current emission standards for incinerators. This list may be extended in the future by newer forms of these devices such as charged droplet scrubbers and high velocity wet precipitators. Most new municipal incinerators built since 1969 have used electrostatic precipitators for particulate emission control. Representative particulate emissions data obtained from the literature for representative refractory wall and water wall incinerators equipped with electrostatic precipitators are presented in Table 51. The electrostatic precipitators appear essential to the operation of the larger municipal incinerators, since without them, the incinerators would be in violation of federal emissions standards.

Description and Operation of other Incinerator Configurations

The large capacity municipal incinerators such as Chicago Northwest generally utilize a single stage mass burn with excess air. Variations exist such as at Ames,

TABLE 50 EFFICIENCY OF DUST-ARRESTING EQUIPMENT

EQUIPMENT	PERCENTAGE EFFICIENCY AT 50 μ	5 μ	1 μ
INERTIAL COLLECTOR	95	16	3
MEDIUM EFFICIENCY CYCLONE	94	27	8
HIGH EFFICIENCY CYCLONE	96	73	27
SPRAY TOWER	99	94	55
ELECTROSTATIC PRECIPITATOR	> 99	99	86
IRRIGATED ELECTROSTATIC PRECIPITATOR	> 99	98	92
VENTURI-SCRUBBER	100	> 99	97
LOW-VELOCITY BAG FILTER	100	> 99	99

SOURCE: D.G. WILSON, EDITOR, "THE TREATMENT AND MANAGEMENT OF URBAN SOLID WASTE," CHAPTER 7, "MUNICIPAL INCINERATION," TECHNOMIC PUBLISHING CO., INC., WESTPORT, CN 06880, 1972.

TABLE 51 PARTICULATE EMISSIONS FROM REPRESENTATIVE INCINERATORS EQUIPPED WITH ELECTROSTATIC PRECIPITATORS

FACILITY	REFUSE CAPACITY TONS/24 HR. DAY	FURNACE TYPE	ELECTROSTATIC PRECIPITATOR REMOVAL EFFICIENCY WEIGHT-PERCENT INLET PARTICLES	EFFLUENT PARTICLE CONCENTRATION** GRAMS/NM^3
NORTHWEST PHILADELPHIA, PA	650	R	98.2, 98.8	0.039, 0.059
SOUTH SHORE #4 NEW YORK, NY	250	R	93.7	0.129
DADE COUNTY NORTHEAST MIAMI, FL	300	R	86.0	0.0623
NORTHWEST CHICAGO, IL	1600	WW	97.3, 97.7	0.053, 0.069
OCEANSIDE HEMPSTEAD, LI, NY	300	WW	98	0.092
HARRISBURG, PA	720	WW	95, 96.2	0.075, 0.104

*R = REFRACTORY WALL, WW = WATER WALL.

**FEDERAL STANDARD = 0.18 GR/NM^3.

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Iowa where shredded refuse is segregated and mixed with coal to become a "Refuse Derived Fuel" (RDF). RDF units generally use single stage burning and, because of the agitation, depend upon a downstream particle control system to remain within emission limits. On the other hand other combustion control techniques are employed in smaller units or in units with specialized applications and these can see service in both municipalities and industrial installations. The alternative configurations can be summarized as: Starved Air and Multiple Chambers, Fluidized Bed, Rotary Kiln, Multi Hearth, Infrared and Molten Salt. The principal features of these units are described below.

Starved Air/Multiple Chamber Incinerators--

These units are used to handle smaller volumes of municipal or industrial wastes than do municipal mass-fired incinerators. In both, combustion takes place in two stages. Solid fuel combustion occurs in an ignition chamber where wastes are dried, ignited, volatilized and partially oxidized into gases and particulates. In the gaseous-phase combustion chamber, volatile components are mixed with secondary air and auxiliary fuel and fired at temperatures in excess of 540°C (1000°F). The principal distinction between older, multiple chamber units and newer, starved air units is in the amount of excess air which each utilizes and their particulate emissions. Multiple chamber units generally operate at 200 to 400 percent excess air. While their particulate emissions are lower than those of mass-fired municipal incinerators, they do, in some cases, require particulate controls. Because of this, most new, small incinerators are starved air units (see Figure 16). These units operate with a less than stoichiometric concentration of air in the primary chamber. This further reduces agitation of the solid mass in the primary chamber, thus reducing particulate emissions below levels of multi-chamber incinerators. As a result, starved air units generally do not require particulate controls.

For the purpose of this study, multiple chamber and starved air units are considered as a single category; carbon fiber emission factors for both are expected to be comparable. This is because while there is less agitation in the primary chamber of starved air units, temperatures there are too low (less than 540°C) to significantly oxidize any fibers that are released and the fiber residence time in the high temperatures of the secondary chamber are short--typically 0.7 seconds. On the other hand, fibers that are released in a multiple chamber unit will experience high temperatures for a longer period of time and therefore a higher percentage of these released fibers will be oxidized.

Fluidized Bed Incinerators--

Presently fluidized bed incineration has received only a pilot plant application to the burning of municipal wastes but represents an established option in handling specialized industrial wastes. The principal features of a fluidized bed incinerator are illustrated in Figure 17. The configuration makes use of a fluidized bed of noncombustible materials (sand or similar particles) kept in suspension by a sufficiently high air flow upward through the bed. The particles are kept in constant motion and behave as a fluid. In operation, finely divided refuse is injected into the bed. The thermal inertia of the bed provides a heat sink for quick drying. The continuous agitation assures good mixing for combustion. When stubborn compounds exist, additional fuel can be introduced to increase the temperature. The continuous rapid agitation of a fluidized bed results in the release of particles. Fluidized bed units have downstream particulate control systems with high efficiency scrubbers generally employed. The action of the fluidized bed makes these incinerators effective in burning sludge, and at the present time the major (75%) utilization is for the consumption of sewage sludge. The specialized nature of these incinerators also limits the number of manufacturers

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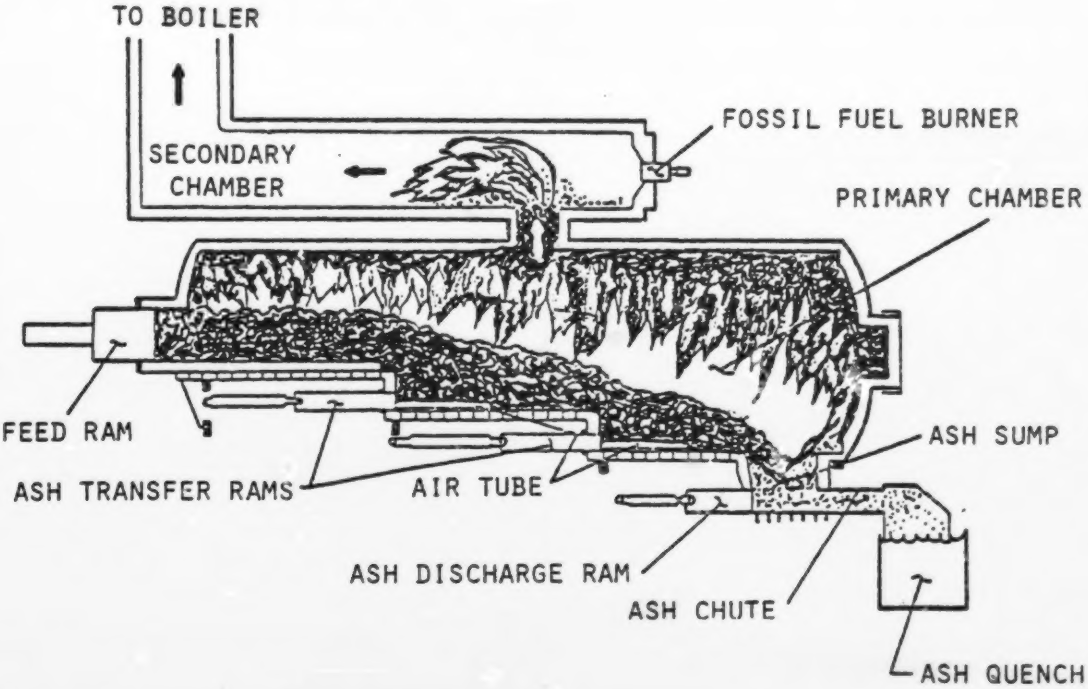

FIGURE 16 CONTROLLED AIR DUAL CHAMBER INCINERATOR

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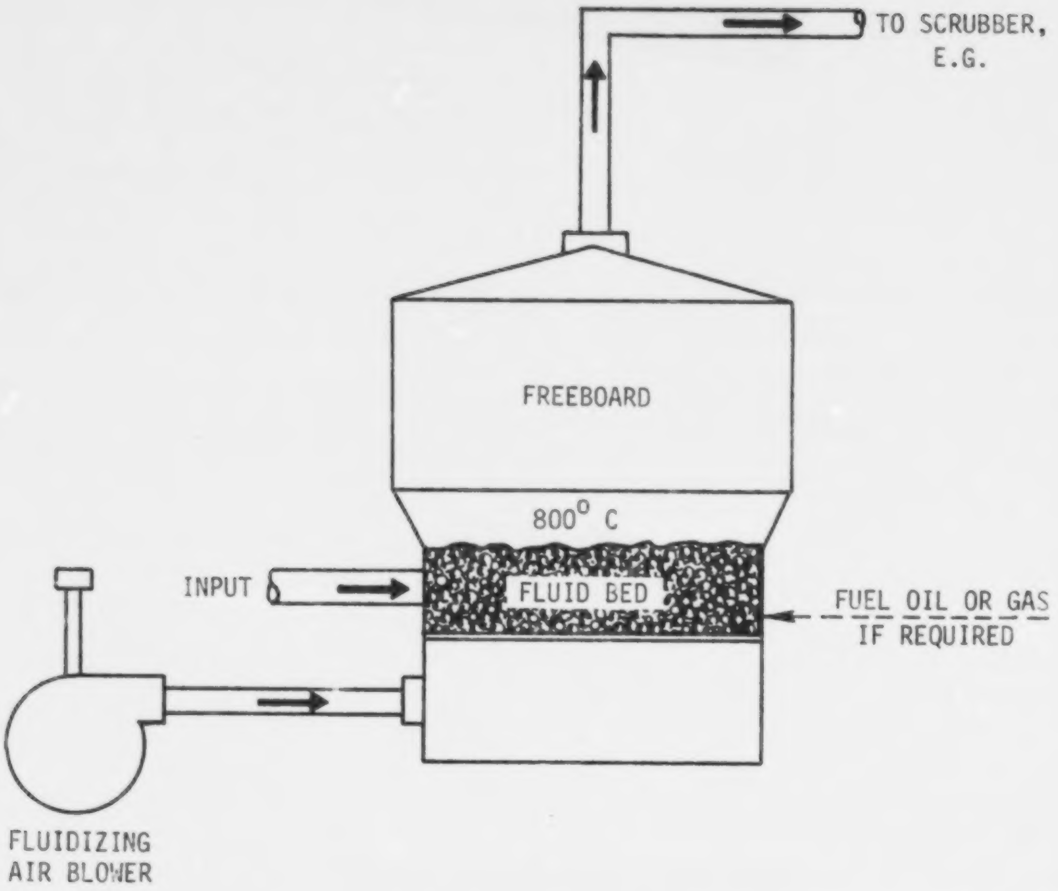

FIGURE 17 FLUID BED INCINERATOR

in the United States. Presently two major incinerator manufacturers offer a range of established designs for fluidized bed incinerators.

Rotary Kiln Incinerators—

These incinerators are used by industry to destroy solids, liquids, sludges and tars. They can also be designed to handle containerized wastes. The Kiln consists of a slowly-rotating, refractory-lined cylindrical tube with one end slightly higher than the other. Rotation causes refuse to move toward the lower end and results in mixing of unburned waste, fuel and oxygen. Combustion temperatures and waste residence times vary greatly, depending on the type of waste being combusted. Most units have an afterburner to insure complete combustion of volatiles. The continuous agitation of these units requires a downstream particulate control system.

Multiple Hearth Incinerators—

These incinerators can also be used to dispose of sludges, tars and solids, but they are most commonly used in sewage plant sludge disposal. The multiple hearth furnace consists of a verticle, refractory-lined circular steel shell with refractory hearths located one above the other, as shown in Figure 18. Sludge and/ or granulated solid combustible waste is fed into the top and falls on a circular hearth. Slowly rotating rabble arms push the refuse across the hearth to drop holes. This process is repeated on lower hearths as combustion occurs until ash finally drops out the bottom. Auxiliary fuel can be utilized to raise the temperature in the central, combustion region. Scrubbers are required for most applications, and afterburners are sometimes used.

Infrared Incinerators--

Infrared incineration represents recent innovation aimed at burning finely divided refuse in a manner which minimizes the output of hot gases and thereby reduces the size for the downstream scrubber. The concept feeds a finely divided wet mix onto a moving porous steel belt. The movement of the belt first allows some dewatering of the mix and then passes under high intensity infrared heaters. The heat completes the drying, does some pyrolization and eventually initiates combustion. The entire process proceeds with the minimum air supply needed to oxidize the refuse. At the present time only one manufacturer produces this type of unit. The principal application has been for sewage sludges; however, the chemical industry is beginning to use these units.

Molten Salt Incineration--

Molten salts are well-established within industrial processes. Molten salt furnaces provide an excellent means for heat treating metal in a chemically inert environment. The reduction of aluminum from its ore is an electrolytic reaction within a molten salt environment. Molten salt incineration based upon the carbonates of lithium, sodium and potassium offers a means to destroy the stubborn compounds associated with the toxic chlorinated hydrocarbons. In such a salt bath the introduction of air will provide the oxygen needed to burn the carbon and hydrogen. The chlorine released will first break down the carbonates to release carbon dioxide and then be retained in the molten salt as the chloride of Li, Na or K. Incinerator systems based upon carbonate salts have been developed and are now advertised by one manufacturer in the United States.

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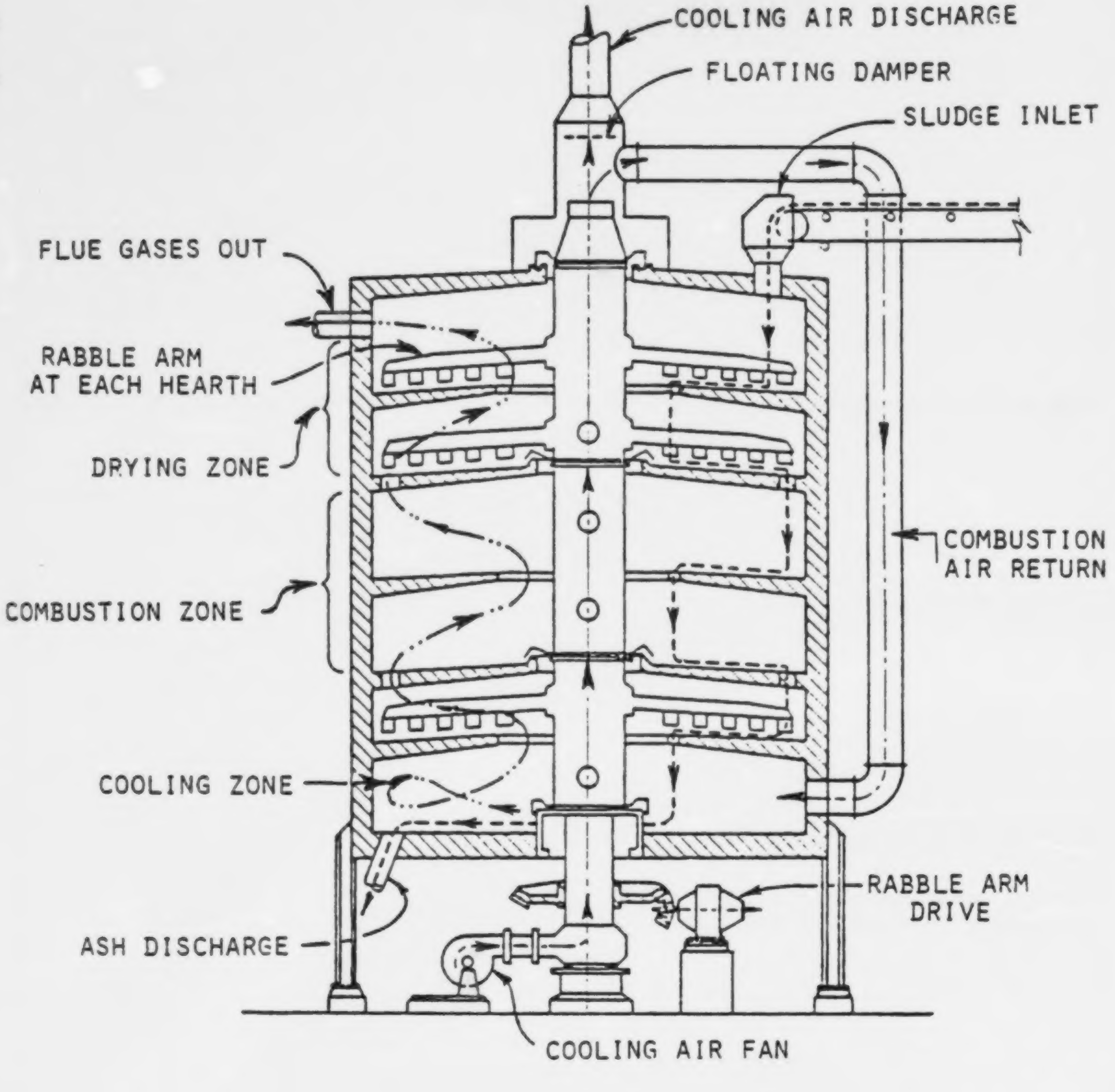

FIGURE 18 MULTI-HEARTH INCINERATOR

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Single Chamber, Conical and Others--

A number of smaller scale single-stage-burn, mass-fired incinerators are operating within municipalities and industry. The municipal units are tending toward extinction; the industrial units tend toward specialized needs of a particular operation such as trash-burner, or burn-away of extra material to recover an item of value. These units tend to have simple feed mechanisms, gravity or manual agitation and no particulate control systems. A special case of these units exists around woodworking plants as conical incinerators. These units resemble an oversized old-style kitchen salt shaker and share about the same degree of design sophistication. In general the units are wood-waste fed by a conveyor belt which dumps the new fuel on top of the burning pile. The unrestricted air supply assures complete oxidation of the waste; the wire mesh which covers the top retains dangerous sparks; otherwise, there is no particulate control system. The usage of conical units is decreasing; however they still persist in areas where woodworking produces a difficult-to-handle, bulky scrap.

IMPACT OF FIBER RELEASES FROM INCINERATORS

Burning of a carbon fiber reinforced plastic device in an incinerator results in the release of free carbon fibers in the flue gas leaving the furnace. The question arises as to what extent these conductive fibers can be arrested by the different particulate control systems available. As part of the Risk Assessment programs conducted by the NASA Langely Research Center and the Department of Transportation, extensive testing and analysis was conducted to estimate the following data: the quantities of fibers released from fires; the efficiencies of filters in removing carbon fibers from air streams; and the economic impact attributed to airborne fibers. The tests and analysis performed as a part of this Risk Assessment program were directed at evaluating the impacts of the accelerated release of carbon fibers into the atmosphere as a result of a fire following a transportation accident. Both aircraft and automobile accidents were considered as potential sources for carbon fiber release. The data from the Risk Assessment program can be used to predict a potential economic impact for carbon fibers released from incinerators. The potential for a measurable economic impact relates to single airborne carbon fibers with lengths of one millimeter or longer. These fibers have the capability to enter into electrical equipment and cause some degree of interruption. The circuitry considered sensitive are those which employ digital logic or similar low voltage, low power elements, such as audio amplifiers, and some of the control units for household equipment.

Fiber Release Data

The NASA Langely Research Center made an extensive study of fibers released from burning composites; their data show that the degree of release relates principally to the amount and type of agitation. Table 52 summarizes the release rates for single airborne fibers 1mm or longer when exposed to an oxidizing environment at temperatures of the order of 1000°C. The materials burned in the NASA test all used epoxy type resins and involved cure cycles employing elevated temperatures and high pressures. The samples were representative of aircraft practice (indeed many of the items were old airplane parts). The exposures to fires included small samples in laboratory test rigs, larger samples in test chambers and actual aircraft parts in outdoor pool fires as a simulation of an accident situation. The release fractions measured relate to the weight of the carbon fiber present in the initial sample of composite and show a range from 0.01 percent to 10 percent. The conditions most representative of municipal incinerators fall between the measurements for mechani-

TABLE 52 SUMMARY OF CARBON FIBER RELEASE DATA FOR ELECTRICAL HAZARD LENGTHS

NASA RISK MEASUREMENTS, SUMMARY	RELEASE FRACTION
• BURN ONLY QUIET AIR	0.01 PERCENT
• MECHANICAL AGITATION	0.1 PERCENT
• LOW VELOCITY AIR--15 M/SEC.	1.0 PERCENT
• HIGH VELOCITY AIR	8 PERCENT
• EXPLOSIVES	10 PERCENT
DOT RISK MEASUREMENTS	
• BURN IN AIR STREAM	0.06 PERCENT

cal agitation, 0.1 percent, and the measurements for low velocity air, 1.0 percent. The Department of Transportation recognized that automotive applications could not accept the slow cure cycles inherent with epoxies; consequently, they made a series of tests using carbon fiber composites based upon a polyester resin. Their results correlate well with the data from the other fire release tests.

All the fire release test results show a consistency relative to the degradation of the resin. If a carbon fiber composite receives an exposure to oxidizing temperatures of the order of 1000°C, the resin will be destroyed and the release of free fibers will correspond to the type or degree of agitation. Up to 80 percent of the released fibers will show a reduction in diameter from oxidation with a 50 percent reduction in diameter as the mean.

A comparison of these release rates with particulate emissions from mass burning of refuse shows an interesting correlation. Measurements of emissions from open pit burnings show a particle release of 0.8 percent (EPA Data Stored in NEDS Files). A review of the documentation which supported the design for the NASA Langley Refuse Fired Steam Generator showed particulate releases from the hot zones of incinerators averaged 1.5 percent mass release. Particulate emissions from mass-burning municipal incinerators have been found to vary from about 0.5 percent by weight to as high as 3.5 percent by weight [79].

On this basis, a conservative estimate for the amount of single airborne carbon fibers released from municipal incinerator fires would be 4 percent of the input mass of carbon fiber contained in the composite. Thus, incinerating 100 kg of fiber in pieces of composites would release 4 kg of free fibers from the surface of the burning refuse. This portion of the release would have lengths longer than 1 mm and at the point of release, could be considered a potential hazard to electrical equipment. Some fraction of these released fibers would find their way through the passages of the incinerator, through the particulate control system and up the stack into the atmosphere. Such fibers would then be carried downwind to fall out over the surrounding area.

Efficiencies of Particulate Control Systems

A cloud of airborne fibers moving within the flow passages of an incinerator will experience an attenuation due to adhesive impacts on walls, or to break up or to capture by particulate control systems. The Risk Assessment defined this reduction in number in terms of a "Transfer Function." The Transfer Function for any filter, flow passage or similar action was defined as that fraction of the input population which emerged as an output. Thus, for the case of window screen, which will remove 70 percent of the fibers from an air stream, the transfer function is 0.3 and corresponds to the 30 percent which will pass through such a screen. Estimates of incinerator transfer functions can be drawn from experience or test data with carbon fibers and must consider four cases as typical installations.

Incinerators Operating with No Active Particulate Control System--

A number of municipal incinerators have no active system for removing particulates from the gas stream but rather employ a passive system. Most of these units are old designs; however, units which employ two-stage burning or employ multiple chambers with afterburning, operate at stack temperatures which preclude the use of an active particulate control system. Tests of passive type dust separators showed very low efficiencies for removal of carbon fibers. Therefore these types of incinerators have been assigned the value of 0.9 for a transfer function. On this basis, conservatively, 90 percent of the fibers released from the fire will appear in the exit plume.

Incinerators with Baghouse Filtration--

A limited number of municipal incinerators employ bag type filters to control particulates and these should provide an effective means for removing carbon fibers from a gas stream. The testing of filter elements during the NASA Risk Assessment study showed that filter element materials generally were more effective in removing carbon fibers than they were in removing spherical particles of the same diameter. Based upon such measurements, a transfer function of 0.01 appears as a usable conservative estimate for incinerators which employ baghouses.

Incinerators Using Wet Scrubbers for Particulate Control--

The EPA compilation of data from scrubber type particulate control systems show a range of effectiveness. Testing in support of the Risk Assessment did not specifically include the effects of wet scrubbers on airborne carbon fibers. On the other hand, a standard fire-fighting fog nozzle proved effective in removing both fibers and soot from the gas stream in one of the test series which evaluated fire release effects.

The shock tube test facility at the Naval Surface Weapons Center, Dahlgren, Virginia, consists of a pipe approximately 500 meters long and 5 meters in diameter. A pool of fire at one end burned composite and carried the airborne fibers to the other end where they were allowed to fall on items of electrical equipment for exposure testing to fire released fibers. A standard fire-fighting fog nozzle at the exit effectively removed all soot particles larger than one micrometer together with the airborne fibers. These results suggest that a transfer function equal to the average for measured systems would be an appropriate conservative value. The average from presently available data establishes a value of 0.3 for the transfer function.

Incinerators with Electrostatic Precipitators--

The interaction of an airborne carbon fiber with an electric field has been well established. The principal laboratory instruments used for counting and measuring the length of an airborne fiber depends upon the fiber moving under the influence of the field and making contact with the high voltage electrode. A measurement of the charge transferred to the fiber and its subsequent repulsion from the electrode provides both the count and the indication of length. In a clean laboratory environment fibers do not stick to the plates of a precipitator. In the mixed environment of an incinerator, fibers are expected to be swept up in the other materials which adhere to the electrodes. An approximation was observed in the survey of the refuse-fired steam generator at the Norfolk Naval Shipyard. This installation employs electrostatic precipitators to remove fly ash prior to discharge up stacks. On occasion the facility processes scrap classified documents through a shredder which blows the confetti into the flame zone of the incinerator. The conductive fly ash from burned paper was observed to enter the precipitators and load the high voltage power supply to the extent the operating voltage dropped by as much as 25 percent (voltmeter readings dropped from 90 kv to 70 kv). Even under such conditions the precipitator contained both the fly ash and the conductive carbon residue from the paper. From these observations it appears reasonable to expect that electrostatic precipitators will contain airborne carbon fibers to the same degree as other particles moving in the gas stream. On the other hand, the CF-bearing material may enter the incinerator in discrete "slugs" producing clouds of particulate with high concentrations of CF. Under these circumstances a greater percentage of this material may pass through the precipitator. In view of these uncertainties, a conservative value of 0.2 will be used for the transfer function through an electrostatic precipitator. This value reflects both the results from EPA data sources and measurements from the qualification runs on a Philadelphia municipal incinerator.

Heat Recovery Incinerators with Electrostatic Precipitators--

The new municipal incinerators represented by installations such as Chicago Northwest and Saugus, Massachusetts use the heat from burning refuse to generate process steam. These newer incinerators all employ electrostatic precipitators in the exhaust gas streams. For these installations (the boilers are of the water tube configuration) the flow passages through the banks of tubing provide many opportunities for impact with walls resulting in adhesion or breakup into shorter (less than 1 mm) lengths. Test measurements show that fiber breakup will occur in cold air at velocities of the order of 30 meters/sec. Normal flow velocities within incinerators are well below those values; however, around boiler tubes the velocities in local turbulences and burbles can reach such levels. In addition, while carbon fibers show exceptional strength properties in tension and compression, they are weak in shear. A turbulent flow field, therefore, offers the opportunity for breakup of fibers. This effect coupled with the large surface area will result in a significant attenuation of fibers. Consequently a transfer function of 0.3 has been assigned to the flow passages through boilers and the overall transfer function through the incinerator becomes the product of the flow passages and the precipitator $(0.3)(0.2) = 0.06$.

The effect on fire released fibers is summarized in Table 53. The comparison assumes 100 kg of fiber as composite is fed into an incinerator of each type.

TABLE 53 COMPARISONS OF POTENTIAL EMISSIONS FROM AN INCINERATOR-FED 100 KG OF COMPOSITE

PARTICLE CONTROL SYSTEM	FIRE RELEASE FREE FIBERS (KG)	TF	STACK RELEASE AS FREE FIBERS (KG)
NO ACTIVE SYSTEM	4	0.9	3.60
BAG HOUSE	4	0.01	.04
WET*SCRUBBER	4	0.3	1.20
ESP	4	0.2	.80
HEAT RECOVERY ESP*	4	0.06	.24

ESP: ELECTROSTATIC PRECIPITATOR

Economic Impacts for Airborne Fibers from Municipal Incinerators

The NASA Risk Assessment program developed models to predict the damage and effects resulting from the release of a quantity of airborne fibers. These models contained the following features and are consequently considered applicable to releases from municipal incinerators.

- Location. The Risk Assessments studied fiber release near airports (major city and small city) and vehicle accidents in municipal areas. These locations are comparable to those for municipal incinerators.
- Dissemination. The dissemination models for dispersion of fibers from fire plumes were based upon those developed by the EPA for industrial and incinerator stacks.
- Impact. The modeling for economic impact includes the effects introduced by buildings and ventilation systems. The quantities of equipment in an area were based on data supplied by both the census and local determinations such as Chambers of Commerce, county business records, zoning regulations, etc. The damage potential and cost data represented the results from testing combined with onsite surveys.

The modeling of communities received two independent analyses. One approach divided the city area into radial rings and segments. Each segmented area was independently assessed for numbers of households, types of business establishments, equipment contained, etc. These data supported the simulations of transport accidents in which a large number (thousands) of simulations were combined to produce a national risk profile. The alternate approach looked at communities as more homogeneous and related the vulnerable equipment to a population density (e.g., density in terms of items per square kilometer). The national risk profiles computed by both techniques were in agreement. These results then provided three elements of data considered applicable to incineration of carbon fibers. These are the Risk Assessment for General Aviation; the Risk Assessment for Ground Transport Accidents; and a specific incident for an airline transport accident. These items are described below.

Risk Assessment for General Aviation Accidents--

The Risk Assessment for general aviation accidents looked at accident scenarios for one year of operation involving American nontransport (general) aircraft. The types of aircraft, quantities of composite and modes of operation were assigned probabilities in accordance with the known distributions. These data permitted the calculation of an average value for the weight of carbon fiber released in a year and an expected value for the costs associated with the fallout of the fiber. The analysis for general aviation predicted an annual average of 85 fire accidents involving composites which would result in a release of 25.92 kg of airborne fibers capable of causing failures to electrical equipment. The expected value for the loss resulting from such a release was $253.00. These results show an average impact of $9.76 for a kilogram of airborne fibers released in an essentially urban community.

Risk Assessment for Transportation Accidents--

The Risk Assessment performed for the Department of Transportation utilized the same statistical model as general aviation but employed a larger number of small releases. These results show an average fire release yearly accident rate of 100,000 incidents which would release a total of 1,326 kg of airborne fiber. The expected loss for such incidents becomes $5,567 and equates to $4.19 average loss attributable to each kilogram of airborne fiber.

Risk Assessment for Transport Aircraft--

The generation of a national risk profile by the simulation technique does not result in data which will permit calculation of yearly averages. The simulations use random draws for a number of parameters with the selection options for each parameter weighted in accordance with statistical distribution. For any of the cities studied, the random draw parameters included aircraft type, location of the accident relative to the airport, the wind direction, the weather conditions and the phase of operation (take off, landing, cruise, static). One representative incident has been identified involving an accident scenario at La Guardia airport with the wind blowing from the east such that the fallout hits the boroughs of Queens and Manhattan. The incident lofted 22 kg of airborne fiber and showed an impact of $178.00. These data show a value of $8.09 damage impact for one kilogram of airborne fibers.

These data appear consistent and suggest an average value of $7.34 as a representative yearly impact cost assignable to a kilogram of airborne graphite fibers from accidental fire release in an urban setting.

Prediction of Incineration Impact Costs

The Risk Assessment data provided a means for assigning an impact cost to a kilogram of airborne fibers originating from accidental fire release and disseminated from a plume type of source. Since the location of accidents and the locations of incinerators will have fallout zones covering essentially the same types of surrounding areas (e.g., cities), the value can be applied to municipal incineration of carbon fiber contained in a composite, and may be calculated in terms of the transfer function through municipal incinerators. Table 54 summarizes these calculations.

These summary values represent the best available predictions for the economic impact on electrical equipment which could result from the burning of carbon fiber composites in municipal incinerators. The determination of the release fraction and transfer function introduced a rational degree of conservatism. The cost value related

TABLE 54 COST IMPACTS ATTRIBUTED TO EACH KG OF CARBON FIBER COMPOSITES BURNED IN MUNICIPAL INCINERATORS

PARTICLE CONTROL SYSTEM	RELEASE FRACTION	TF	COST	YEARLY IMPACT COST/KG
NO ACTIVE SYSTEM	0.04	0.9	7.34	0.264
BAGHOUSE	0.04	0.01	7.34	0.003
WET SCRUBBER	0.04	0.3	7.34	0.088
ELECTROSTATIC PRECIPITATOR	0.04	0.2	7.34	0.059
HEAT RECOVERY	0.04	0.06	7.34	0.018

to dissemination and interaction with equipment carry a similar appropriate conservatism (e.g., rain is not considered as a reducing effect on airborne fibers). All electrical failures are considered as caused by single fibers. Therefore predictions for economic effects based upon these data would carry the same relative conservatism as those produced for the NASA and DOT Risk Assessment.

Carbon Fiber Releases from Industrial Incinerators

The analysis of industrial incinerators untilized the results from the studies of municipal units but recognized the differences in waste streams, types of incinerator and operating conditions. The analysis began with a survey of the industrial incinerators within the United States.

The survey of industrial incinerators provided data which actually supported two analytical predictions. The first prediction estimated the population and types of industrial incinerators which could have carbon fiber scrap mixed into their waste streams. The second analysis evaluated the incinerator operating conditions, the flow passages and the particulate control systems toward predicting the emission of airborne carbon fibers and estimating the potential economic impact. The survey began by canvassing the present manufacturers of industrial incinerators to obtain operating parameters, configuration details and their assessments of current utilization by industrial operations.

The canvass of manufacturers and the results of a previous EPA study [80] show only a few thousand industrial incinerators operating within the United States. The responses from incinerator manufacturers indicated that recent legislation for control of hazardous waste has increased the sales of new units. These newer designs address hard-to-burn wastes and operate at higher temperatures and with longer dwell times than for the older units. The manufacturers of incinerators all seem to recognize the need for such extra capabilities. In their opinion the justification of the expense appears to require the additional benefits associated with either the elimination of hazardous materials, the recovery of energy or the recovery of some valuable constituent in the scrap (i.e., the recovery of silver from scrap x ray film). The newer industrial incinerators, therefore, appear to be potentially effective in oxidizing any carbon fiber scrap. In addition, the combination of either heat recovery or a good particulate control system tends to inhibit the discharge of any airborne carbon fibers which would be released from the hot zones.

The analysis to predict the potential releases of airborne carbon fibers from industrial incinerators followed the steps and technique developed during the previous evaluation of municipal incinerators. In addition, the continuing analysis of fire release data by NASA has provided a means to include the effects of oxidation on the released fiber. The change in the electrical resistance of a carbon fiber due to reductions in diameter becomes a measurable effect when considering industrial incinerators intended to consume hard-to-burn types of waste. The resulting transfer function which relates the input weight of carbon fiber to the effective weight of electrically interactive airborne fibers consists of three terms. These terms and the resulting economic impact potential are summarized in Table 55 and show the values relative to the types and configuration options present within current industrial incinerators. The following paragraphs outline the evaluations or considerations leading to the assignment of the values listed.

Release Fraction--

The fire release testing conducted by NASA in support of the Graphite Fiber Risk Analysis also provides the data base for evaluating the hot zones of industrial incinerators. The temperatures and dwell times for all incinerators exceed the conditions to decompose or burn out any polymeric-based matrix material. The release of single fibers longer than one millimeter (electrically interactive) again relates primarily to the degree of agitation, and industrial units show a wider range of agitation. For aircraft fires the agitation could result in a release fraction ranging from 0.01 to 0.03. The maximum case involves the burst of a fuel tank during the fire. The mass balance for fire release testing has been summarized and appears as Figure 19 [81]. In assessing industrial incinerators, the release rates shown in Table 55 were used for comparison based upon the following observations. Both industrial and municipal designs for multiple chamber incinerators operate within minimum agitations in the fire zone. Their release rates have been previously estimated as half that for an aircraft fire [82]. In a similar manner, fluidized bed and multiple hearth units both employ continuous agitation; one proceeds rapidly with a short burn time, the other more slowly with a longer burn time. Industry sources indicate a 0.01 release fraction to be representative of these units. The infrared configuration burns from a moving belt; the conditions appear equivalent to mass-fired incinerators and have been assigned the same value. In a molten salt unit oxidation proceeds submerged and only gases evolve. For single chamber, conical and other types in industrial use, the release fraction reflects a degree of agitation in excess of that present in mass-fired units but not extreme or continuous as in a kiln or a fluidized bed.

Oxidation Effects--

When carbon fibers are exposed to the high temperature of incineration the individual fibers may be oxidized with a resultant decrease in diameter. The analysis of carbon fibers released from fires has shown that up to 80 percent of the fibers experience some reduction in diameter. The average diameter is reduced by about 50 percent. The evaluation of electrical resistivities for such fibers shows the resistance increases in proportion to the reduction of the cross section area. Thus a 50 percent reduction in diameter causes a fourfold increase in the electrical resistance of a fiber. The vulnerability studies of electrical equipment have shown that the precipitation of an electrical failure is sensitive to the resistance presented by the

TABLE 55 SUMMARY OF INDUSTRIAL INCINERATORS EFFECTS TRANSFER COEFFICIENTS					
TYPE	RELEASE FRACTION	OXIDATION	P.C. SYSTEM	NET	IMPACT COST $/KG OF CF INPUT
MULTIPLE CHAMBER AND STARVED AIR STANDARD	0.005	0.8	0.9	3.6×10^{-3}	0.0264
WASTE HEAT REC.	0.005	0.8	0.3	1.2×10^{-3}	0.0088
FLUIDIZED BET STANDARD UNIT	0.01	0.8	0.1	0.8×10^{-3}	0.0059
WASTE HEAT REC.	0.01	0.8	0.03	0.24×10^{-3}	0.0018
MULTIPLE HEARTH STANDARD UNIT	0.01	0.6	0.1	0.6×10^{-3}	0.0044
WASTE HEAT REC.	0.01	0.6	0.03	0.18×10^{-3}	0.0013
INFRARED UNIT	0.01	0.3	0.1	0.3×10^{-3}	0.0022
MOLTEN SALT	0	0	0	0	0
ALL OTHER	0.015	0.6	0.9	8.1×10^{-3}	0.0594

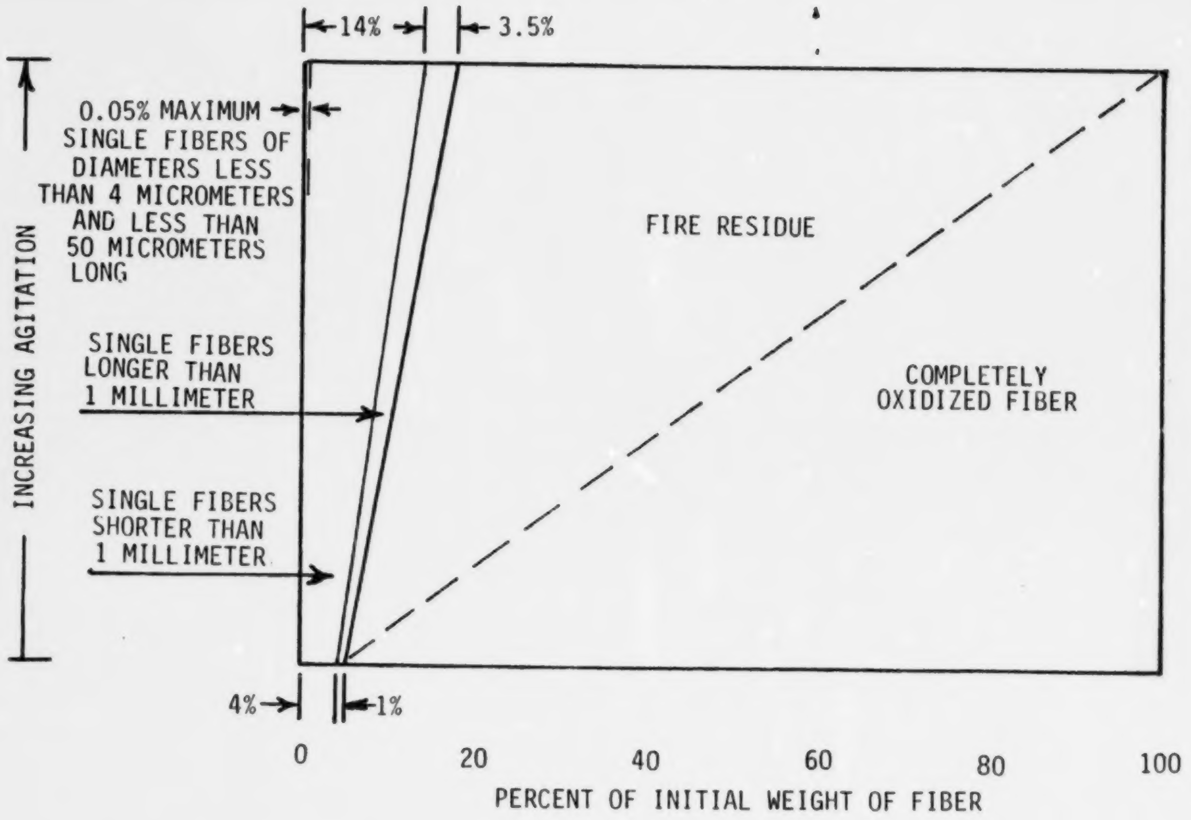

FIGURE 19 MASS BALANCE FOR CARBON FIBERS FROM BURNED COMPOSITES

shorting path. If the resistance is too high, the resulting disturbance would not upset the electrical functioning sufficiently to induce a failure. Thus a reduction in diameter from oxidation reduces the failure causing potential for airborne carbon fibers. The oxidation coefficient shown in Table 55 represents that fraction of the fiber that is not significantly reduced in diameter by oxidation. Thus, an oxidation coefficient of 0.8 indicates that 80 percent of the fibers are reduced in diameter by less than 50 percent, while 20 percent of the fibers are reduced in diameter by 50 percent or greater. The values selected for incinerators (see Table 55) represent conservatism relative to the measurements from pool fire results. These follow the recommendations of a consultant familiar with the oxidizing characteristics of incinerators. The lower values listed for the more complex incinerators recognizes the extra exposure to oxidizing conditions inherent with such incinerators.

Particulate Control System--

The transfer coefficients for the particulate control system followed the same rationale employed for municipal incinerators. The multichamber units have no active systems and depend upon temperature plus control of agitation to keep particulate emissions within limits. The fluidized bed, multihearth and infrared units are built with good control systems, primarily high efficiency scrubbers (see Table 55) since these units are often required to control gaseous constituents in the exhaust stream as well as particles.

Net Transfer Coefficient and Impact Costs--

The coefficient which then relates the weight of carbon fiber fed into the incinerator to an effective weight of electrically interactive airborn fiber is the product of the three factors. The impact cost per kilogram of electrically interactive airborne carbon fiber was previously established as $7.34. Therefore the impact costs which relate to a kilogram of fiber fed into an industrial incinerator becomes the product of the net transfer function times $7.34.

Estimate of the Industrial Incinerator Population Subject to Carbon Fiber Scrap

The results of the canvass of incinerator manufacturers indicated that only a few thousand units were operating within the industrial installations across the United States. A recently published survey by the EPA [80] makes a projection for the national population in terms of the 20 Standard Industrial Classifications (SIC) for manufacturing industries. These data plus the results from the canvass of manufacturers appear summarized in Table 56. The analysis to identify those incinerators which could have carbon fibers in the waste streams proceeded as four general steps.

Types of Incinerators Within Each Class of Industry--

The results of the EPA study 80 showed that in general about 80 percent of the industrial incinerators were starved air or multiple chamber units; the fluidized bed, rotary kiln, multiple hearth and other configurations represented the smaller fraction and showed a degree of specialization to particular industrial operations. The results from the canvass confirmed that general ratio. In addition, for the fluidized bed, multihearth and infrared units, the cooperation obtained from the manufacturers permitted the assignment of specific units to particular industrial operations. These data ranged from published listings which showed numbers of installed units within types of industry to copies of installation lists containing the unit size and the specific industrial facility for the installation. These data and results allowed the establishment of a distribution for incinerator types within each of the 20 major manufacturing

TABLE 56 PREDICTIONS OF INDUSTRIAL INCINERATOR POPULATION BY SIC CLASSIFICATION, EPA REPORT SOURCE DATA

SIC	INDUSTRY	INCINERATORS	SIC	INDUSTRY	INCINERATORS
20	FOOD	33	30	RUBBER/PLASTIC	77
21	TOBACCO	5	31	LEATHER	0
22	TEXTILES	30	32	STONE-GLASS-CLAY	58
23	APPAREL*	88	33	PRIMARY METAL*	180
24	LUMBER	592	34	FABRICATED METAL*	366
25	FURNITURE*	78	35	MACHINERY	475
26	PAPER	57	36	ELECTRIC	313
27	PRINTING	194	37	TRANSPORTATION (INCL. MOTOR VEHICLES, AIRCRAFT, ETC.)	167
28	CHEMICAL	190	38	INSTRUMENTS	46
29	PETROLEUM	23	39	ALL OTHER	255

*NO CARBON FIBER SCRAP FROM THESE INDUSTRIES.

classifications (two-digit SIC). Incinerators were grouped into five general classifications based upon the configuration of the hot zones. These are starved air and multiple chamber, fluidized beds, multihearth/rotary kiln, infrared and single chamber or conical.

Identification of Scrap Sources--

The potential sources for carbon fiber scrap were identified by an in-depth review of industrial operations within each of the major SIC classes. A previous literature search [82] had identified the potential industrial uses for carbon fiber-based composites, and these products were identified in terms of both the using and producing industries. The identification then classified the type of scrap which could originate from such an industry and listed scrap type in terms of the SIC for that particular industry. As examples, in food processing carbon fiber composites are used in picking and peeling machinery for canning and preserving. Thus this type of application could produce broken part scrap for all of the industrial operations listed under SIC 203, Canned and Preserved Fruits and Vegetables [83]. In a similar manner the manufacture of sporting goods will result in production scrap, sporting goods appear as SIC 3949, Sporting and Athletic Goods not Elsewhere Classified. To the extent possible, potential sources of carbon fiber scrap and the type of scrap were identified down to the four-digit SIC level. The classification of scrap considered four general types:

- Worn out or broken parts from machines or equipment (pickers, peelers, loom shuttles, pump impellers, gears, etc.). These items would enter a waste stream as cured composite materials.
- Scrap from composites used for corrosion resistant parts (pipes, linings, valves, etc.). Material would enter the waste stream as broken parts of cured composite. The matrix resin would be different from structural parts.
- Scrap from the manufacture of packing and gaskets. (The Department of Commerce identified this as significant usage.) This material could take all forms: tow, prepreg and composite.
- Scrap from manufacture of equipment (aircraft to sporting goods). Scrap can be as two, prepreg, part cure, full cure, reject parts, etc.

Predictably, the major industrial classes showed a range for potential usage of carbon fiber-based products. The equipment and operations associated with the manufacture of apparel (SIC 23), furniture (SIC 25), primary metals (SIC 33) and fabricated metal (SIC 34) could not identify any candidate opportunities for the use of carbon fiber-based composites. On the other hand, high speed production machinery represents an area of potential application for such composites. Accordingly, worn parts could appear from the operations associated with tobacco products (SIC 21), textile mill products (SIC 22) and printing/publishing (SIC 27). Industries which contend with corrosive environments also become candidates for use of carbon fiber composites in valves, pipe linings and corrosion resistant packing or gaskets. Thus paper (SIC 26), chemical (SIC 28), petroleum (SIC 29) and rubber/plastics (SIC 30) became general candidates for producing scrap. For the other ten general classifications, specific subclasses of industries appeared as the candidates for usage or actual users of carbon fiber composites.

Incinerators Subject to Carbon Fiber Scrap--

Seven of the major manufacturing classifications are general candidates for use of carbon fiber-based composites; therefore all the incinerators in those classifications are considered subject to carbon fiber scrap. For the ten classifications, when the candidate industries were in subclassifications (three-digit or four-digit SIC), the estimate was based upon a proportion of establishments calculation. The last completed census of manufacturers [84] includes a national summary containing the number of industrial establishments with more than 25 employees. This summary extends down to the four-digit SIC level. The use of these data for estimating the numbers of incinerators subject to carbon fiber scrap made the following assumptions:

- Within any major industrial classification (two-digit SIC), incinerators are uniformly distributed among establishments having more than 25 employees (the larger operations)
- A ratio to define the number of incinerators subject to carbon fiber scrap consists of the number of establishments in the candidate subclassifications (three- and four-digit SIC) divided by the total number of establishments in the major industrial classifications (two-digit SIC).

This calculation introduces an element of conservatism. In some of the four-digit SIC classifications not all the operations may be candidates for use of carbon fiber-based composites, yet all the incinerators attributable to that four-digit class are considered subject to carbon fiber scrap. As an example, SIC 3949 manufacture of sporting and athletic goods covers all items from ammunition belts and archery to toboggans and wading pools. The summary lists 463 establishments in this SIC and accounts for approximately 12 percent of the 3,754 establishments contained in all of SIC 39 (other industries). Thus sporting goods manufacturers could account for 31 incinerators (0.123 * 255, see Table 56). This value appears conservative since SIC 3949 includes basketballs, footballs, baseballs and baseball gloves--all items not subject to the use of carbon fiber composites. On the other hand, the degree of conservatism eludes calculation since incinerators are used by the larger manufacturers who usually produce a wide range of products, and some of the companion items such as ski poles and tennis racquets could be a carbon fiber-based product.

Summary Listing--

The numbers of incinerators subject to carbon fiber scrap and the types of scrap potentially entering their waste streams appear summarized in Table 57. The values listed for the dual chamber units reflect the distribution proportion reported in the EPA study [80]. The values assigned for the fluidized bed, multihearth/rotary kiln and infrared were derived from the canvass of manufacturers. The single chamber or conical units were estimated from the results of the EPA study [80], with the conical units all considered as located in woodworking types of operations.

TABLE 57 POPULATION OF INCINERATORS, RELATED TO SOURCE OR TYPE OF CARBON FIBER SCRAP

TYPE OF SCRAP MOVING IN WASTE STREAM	STARVED AIR AND MULTIPLE CHAMBER	FLUID BED	MULTIHEARTH ROTARY KILN	INFRARED	SINGLE CHAMBER OR CONICAL
WORN OUT PARTS FROM PROCESS MACHINERY	359	5	3	2	39
REPLACEMENT OF VALVES, PACKING AND LININGS FROM PIPE	255	23	9	3	0
SCRAP FROM MANUFACTURE OF PACKING AND GASKETS	4	0	0	0	0
SCRAP FROM THE MANUFACTURE AND ASSEMBLY OF PRODUCTION ITEMS	353	0	0	0	35
TOTAL NUMBER OF UNITS	771	28	12	5	74
PERCENT OF POPULATION	89	2.6	1.1	0.5	6.8

SECTION 8

RELATED POTENTIAL PROBLEM AREAS

CARBON FIBER RELEASE DUE TO SHREDDING OF MUNICIPAL SOLID WASTE

Increasingly, shredding is being considered as a necessary first step in the processing of municipal solid waste. After shredding, refuse is much easier to handle and process further because it has a smaller particle size range, more uniform density, smaller bulk (bulk volume is reduced by half) and is thoroughly mixed and more homogeneous. The September 1979 survey of resource recovery activities in the United States by the National Center for Resource Recovery, Inc. (NCRR), Washington, DC [85] indicated that shredding was an inherent part of the process at 24 of the 36 locations listed as being either operational or under construction at the time of the survey. Of the 24 facilities with shredders, a total processing capacity of approximately 23,000 metric tons/day (25,000 TPD) of municipal solid waste is achieved. The survey indicated that by the end of 1980, at least 21 of these facilites with a combined capacity of 19,000 metric tons/day (21,000 TPD) of municipal solid waste would be in operation. The 1979 NCRR survey also listed an additional 24 localities which would be installing new resource recovery facilities in the future. These localities were reportedly either in advanced planning stages or negotiating with bidders/contractors. It could be expected that shredders would be used at the majority of these facilities.

Shredders have the potential for producing explosions that could result in the release of carbon fibers into the atmosphere if carbon fiber containing composites were present in the municipal solid waste being processed. Size reduction by shredding employs either horizontal or vertical hammers to cut, tear and rend the heterogeneous municipal solid waste. Impact with various materials produces sparks so there is a definite ignition source present almost continuously. If the material in the shredder has a sufficiently low ignition temperature, a fire or explosion will follow. The principal sources of fire and explosion are containers filled with gasoline or other volatile liquids that form explosive mixtures with air and dusts formed by shredding municipal solid waste and discarded explosives.

A detailed analysis of the frequency of explosions in refuse shredders by Factory Mutual Research, as reported by Pyle [86], indicates an explosion incident for every 77,000 metric tons (85,000 tons) of waste processed. Based on this value and on the annualized total combined capacity of all the municipal solid waste treatment facilities equipped with shredders in the NCRR survey, (25,000 TPD x 250 days/year) = 6.2×10^6 tons/year or 5.6×10^6 metric tons/year), one would anticipate the occurrence of 74 shredder explosion incidents per year.

The typical processing capacity of a refuse shredder ranges from 15 TPH to 50 TPH [87]. It is estimated that the average residence time of refuse in a shredder may range from a few seconds to possibly as much as 30 seconds. This residence time, and the hourly capacity, establish the instantaneous amount of refuse present in a shredder that presumably would be vented into the atmosphere in the event of an explosion. Assuming a residence time and a shredding capacity of 15 seconds and 45 metric tons/hour, (50 TPH) which is at the upper end of the range, a high estimate for the instantaneous refuse content of a shredder is 45,000/hr X 15/3600 hr = 190 kg.

If it is assumed that all the refuse present in the working volume of a shredder is vented into the atmosphere when an explosion occurs, then, with the above, 190 kg of refuse are vented per shredder explosion. On an annual basis, based on 74 explosions per year, slightly over 14 metric tons of refuse would be introduced into the atmosphere as a result. On a percentage basis, these 14 metric tons represent only 2.5×10^{-4} percent of the total 5.6×10^{6} tons of municipal solid waste processed by the facilities.

Using the projected disposal of 600 metric tons of carbon fiber in the municipal waste stream and a total solid waste stream of 175,000,00 metric tons per year, the expected value of the average carbon fiber content of the municipal solid waste in 1990 will be 3.4×10^{-4} percent. Based on this expected carbon fiber content, a shredder would have an instantaneous carbon fiber content of 0.65 grams. Should an explosion occur, this carbon fiber would be vented into the atmosphere. However, according to NASA's data on the disposal of carbon fibers under explosive conditions, only 10 percent of these fibers, or 65 mg, would be released into the atmosphere. Taking once again the average value of $7.34 per kg of released carbon fibers as the economic cost of carbon fiber release, the economic cost of a carbon fiber release as the result of a shredder explosion would be $0.0005--approximately 1/20 cents per explosion, or $0.04 per year for the 24 resource recovery systems listed in the NCRR survey. If all the municipal solid wastes generated in 1990 were shredded and current explosion statistics applied (one explosion per 85,000 tons), approximately 2,260 shredder explosions would be anticipated. Even in this case the projected annual economic cost of carbon fiber released into the atmosphere as a consequence of the explosions would amount to 2,260 X $.04 = $1.13.

It can thus be concluded that the economic cost of carbon fiber release due to the explosion of refuse shredders will be insignificant.

CARBON FIBER RELEASE DUE TO LANDFILL FIRES

Landfills are the most prevalent method of disposing of solid municipal waste, with approximately 89 percent of all municipal wastes being disposed at approximately 11,000 landfill sites. (In addition, there are approximately 3,000 landfills for industrial wastes [88]). Fires in landfills are a common hazard which could result in the uncontrolled generation of airborne carbon fibers if a significant quantity of carbon fiber composites were present in the landfill. In 1978, according to the U.S. Fire Data Center [89], there were approximately 37,000 fire occurrences at municipal and industrial dumps and landfills. This corresponds to an average of one fire per dump or landfill every 20 weeks. Since solid wastes accumulate in a dump over a period of time, an extensive dump fire could consume a significant amount of solid waste. The potential release of carbon fibers in the atmosphere could be significant, since it would be a function of the cumulative amount of carbon fiber containing composites present in the area.

No data were found as to the size, duration and extent of landfill fires, i.e., how much trash is consumed in these fires, how long these fires last and how great an area is covered by a fire. These data are necessary to develop quantitative estimates of the potential release of carbon fibers that would result, and of the economic damage.

According to the U.S. Fire Data Center [89], the average cost of a landfill fire is very low, $87 per occurrence. This is only 1 percent of the average cost of other types of fires. This cost represents the damages occasioned by the fire in terms of equipment and property loss at a landfill, damage due to smoke, etc. Little or no value is included for the trash consumed by the fire.

It appears that most landfill fires, if handled rapidly, involve small conflagrations. It is also true that in a landfill, a fire, once it has taken hold, may smolder on for many years and can become extensive. In this case fire officials have found no certain way of dealing with this problem short of massive digging [90]. The problem of extensive fires in sanitary landfills appear to be less severe than with open dumps. The cellular structure of a basic sanitary landfill prevents a fire from traveling very far, and the sealing of the top of the cell may be enough to starve a fire sufficiently to put it out.

In the absence of precise data, the next best indicator is an estimate of the upper bound to the economic cost that would result from the release of carbon fibers into the atmosphere as a result of the burning of carbon fiber composites in a dump fire.

It is reasonably conservative to assume that as much as 1 percent of the municipal solid wastes that go into a landfill each year are consumed by dump fires. Using the projected disposal of 600,000 kg per year of carbon fiber in 1990, and 89 percent of this material being disposed in landfills, with the 1 percent fire consumption assumed, approximately 5,300 kg per year of carbon fiber would be involved in landfill fires. The release of particulates from the open burning of municipal refuse is rated at an emission rate of 8 kg per metric ton, or 0.08 percent by weight [91]. Assuming that carbon fibers are released in the same ratio, the burning of 1 percent of annual municipal waste accumulation in landfills would result in the release of 43 kg per year of carbon fiber into the atmosphere. Based on an economic penalty of $7.34 per kg of fibers released, this would correspond to a total annual economic cost of $314. This is a negligible amount. Furthermore, it is to be noted that even if all the carbon fiber composite material entering landfills were to be involved in fires, the total economic cost of carbon fiber damage would be $31,400, which is less than 1 percent of the estimated $3,200,00 cost currently associated annually with landfill fires. It can thus be concluded that the economic cost of carbon fiber release due to landfill fires will be negligible.

SECTION 9

RESULTS AND DISCUSSION

Now that the economic cost (per kg) of carbon fiber disposal has been estimated for each type of incinerator and its particulate control system, the economic impact of the disposal of consumer products containing carbon fiber by incineration can be computed for given carbon fiber demand, fraction incinerated and incinerator mix. In order to estimate this impact in the post-1990 period, the forecast of carbon fiber demand for consumer products in 1990 will be used as the basis for estimating a post-1990 disposal load. Since the useful life estimates vary widely for many of these consumer products, a conservative basis will be used to estimate the post-1990 disposal load. It will be assumed that all of the carbon fiber used in the manufacture of consumer products in 1990 that will eventually enter the municipal waste stream in the post-1990 time period, enters the municipal waste stream in a given year in this time period (see Section 5, U.S. Production and Consumption of Carbon Fiber Material). A baseline case can be created for both the municipal and the industrial sectors by assuming the current fraction of solid waste incinerated and the present mix of incinerators to hold. As landfill sites become increasingly scarce and the natural resources and energy reserves of this country are depleted, it is reasonable to anticipate an increase in the fraction of waste incinerated in an effort to reduce waste volume while recovering both resources and energy. For the same reasons as well as a growing awareness of the necessity of air pollution control, the number of incinerators in use in this country may be expected to increase and the mix to change. A total of five different scenarios are thus considered and analyzed for their potential economic impacts first in the municipal sector and then in the industrial sector.

DEFINITION OF ALTERNATIVE SCENARIOS FOR MUNICIPAL SOLID WASTE DISPOSAL

Scenario No. 1--Baseline Case

As mentioned above, a baseline case can be established by assuming the current fraction of solid waste incinerated and the present mix of municipal incinerators to exist in 1990. Since the projected use of carbon fiber in consumer products for 1990 is estimated to be 600 metric tons (see Section 5), and only 4 percent of all municipal waste is presently incinerated, the baseline case considers a total of 24 metric tons/yr of carbon fiber to be incinerated, or 80 kg per day, assuming a 300-day year (i.e., 600 x 0.04). The carbon fiber is assumed to be distributed uniformly throughout the waste with the same fraction of waste processed by each type of incinerator as today. The latter data as well as the actual mix of incinerators in use today was obtained from an updated version of the Alvarez survey originals conducted by the Office of Solid Waste Management [92]. This report shows that a total of 41 incinerators are currently operating including:

- Eight with no active particulate control system
- One with bag house filtration
- Eight with wet scrubbers
- Eleven with electrostatic precipitators
- Thirteen with both heat recovery and electrostatic precipitators.

For each type of incinerator the economic cost of carbon fiber disposal is computed as the product of the amount processed by the incinerator type and its impact cost, as determined in Section 7. The resulting costs per day and per year (assuming a 300-day year) are shown in Table 58. The total yearly cost of Scenario No. 1 is obtained by summing over all incinerator types and can be seen in Table 58 to amount to approximately $1700, a negligible sum.

Scenario No. 2--Near-Future Case

As new landfill sites become increasingly difficult to find and resource recovery is emphasized as an important part of national energy policy, the number of incinerators in use in this country can be expected to increase. In fact, the addition of ten resource recovery facilities with electrostatic precipitators is already planned for the near future, according to recent articles in Resource Recovery Activites [93, 94]. These ten additional resource recovery facilities are thus added to the baseline incinerator mix in order to set up a realistic near-future case. It is furthermore assumed that 5 percent of total waste is incinerated, in order to justify the use of new equipment. As shown in Table 59, a total of 100 kg of carbon fiber is then processed daily, leading to a total annual cost of approximately $1,830 for the post-1990-period disposal, again a negligible figure.

Scenario No. 3--Far-Future Case

As time progresses further, five additional resource recovery facilities with electrostatic precipitators should be installed, according to the plans described in

TABLE 58 ECONOMIC IMPACT OF SCENARIO NO. 1

PARTICULATE CONTROL	NUMBER OF UNITS	KG PER DAY	COST PER KG ($)	COST PER DAY ($)	COST PER YEAR (300 DAYS) ($)
NONE	8	9.4	0.264	2.48	744.0
BAG HOUSE	1	0.7	0.003	0.002	0.6
WET SCRUBBERS	8	12.2	0.088	1.074	322.2
ELECTROSTATIC PRECIPITATOR	11	25.6	0.059	1.51	453.0
HEAT RECOVERY WITH ELECTROSTATIC PRECIPITATOR	13	32.1	0.018	0.578	173.4
TOTAL		80			1693.2

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TABLE 59 ECONOMIC IMPACT OF SCENARIO NO. 2

PARTICULATE CONTROL	NUMBER OF UNITS	KG PER DAY	COST PER KG ($)	COST PER DAY ($)	COST PER YEAR (300 DAYS) ($)
NONE	8	9.6	0.264	2.53	759.0
BAG HOUSE	1	0.7	0.003	0.002	0.6
WET SCRUBBERS	8	12.5	0.088	1.1	330.0
ELECTROSTATIC PRECIPITATOR	11	26.1	0.059	1.54	462.0
HEAT RECOVERY WITH ELECTROSTATIC PRECIPITATOR	23	51.1	0.018	0.92	276.0
TOTAL		100			1827.6

Resource Recovery Activities [93, 94]. By then the old incinerators without any particulate control or with a bag house filter or wet scrubbers will have been phased out. None of these will be replaced, as it is not economical to make them meet federal environmental specifications. The far-future case, therefore, includes eleven electrostatic precipitators on nonrecovery plants, as exist today, and a new total of 28 electrostatic precipitators on resource recovery facilities as shown in Table 60. The fraction of total waste incinerated is assumed to increase as above to 8 percent, leading to 160 kg of carbon fiber incinerated daily. It can be seen in Table 60 that the total annual economic impact of carbon fiber incineration is then of even less significance, amounting to approximately $1,200 nationally.

TABLE 60 ECONOMIC IMPACT OF SCENARIO NO. 3

PARTICULATE CONTROL	NUMBER OF UNITS	KG PER DAY	COST PER KG ($)	COST PER DAY ($)	COST PER YEAR (300 DAYS) ($)
NONE	0	0			
BAG HOUSE	0	0			
WET SCRUBBERS	0	0			
ELECTROSTATIC PRECIPITATOR	11	26.9	0.059	1.59	477.0
HEAT RECOVERY WITH ELECTROSTATIC PRECIPITATOR	28	133.1	0.018	2.4	720.0
TOTAL		160			1197.0

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Scenario No. 4--Intensive Energy Recovery

The amount of solid waste converted to energy as of 1977 in certain European countries is as follows [95]:

Country	Percent of solid waste converted to energy
Denmark	60
Switzerland	40
Netherlands	30
Sweden	30
Germany	20
England	10

In stark contrast, only 1 percent of solid waste is recovered as energy in the United States. This is mainly due to the fact that the historic relative cost of energy in the United States is much lower than in Europe. However, should the cost of energy rise enough to make resource recovery competitive with landfilling and to promote additional research on energy recovery technology, it is conceivable, at least in theory, that the present institutional barriers to planning and implementing resource recovery would be overcome and that as much as 60 percent of total waste could be incinerated in this country too. This case is presented in Table 61, where a total of 1,200 kg of carbon fiber are processed daily in incinerators with electrostatic processors only, as it is not likely that this case could occur until after the less efficient equipment has been phased out due to the amount of time necessary to plan and install such an expanded system. The annual cost associated with this scenario is about $6,795.

TABLE 61 ECONOMIC IMPACT OF SCENARIO NO. 4

PARTICULATE CONTROL	KG PER DAY	COST PER KG ($)	COST PER DAY ($)	COST PER YEAR (300 DAYS) ($)
NONE	0			
BAG HOUSE	0			
WET SCRUBBERS	0			
ELECTROSTATIC PRECIPITATOR	25.6	0.059	1.51	453.0
HR W/ESP*	1174.4	0.018	21.14	6342.0
TOTAL	1200			6795.0

*HEAT RECOVERY WITH ELECTROSTATIC PRECIPITATOR

Scenario No. 5--Upper Bound Case

Even if all municipal waste were incinerated, and a total of 2,000 kg of carbon fiber were thus disposed of by incineration daily (requiring a total of 948 new incinerators at present capacity!), the total annual economic impact would be $27,306 nationally (Table 62), which is still negligible.

NATIONAL ECONOMIC IMPACT OF CARBON FIBER INCINERATION UNDER ALTERNATIVE SCENARIOS FOR MUNICIPAL SOLID WASTE DISPOSAL

A total of five different scenarios of the municipal incineration of carbon fiber were considered and analyzed for their potential national economic impact. The results are summarized in Table 63. The fraction of waste incinerated and the mix of air pollution control devices on the incinerator were varied simultaneously, but it is still clear that as the percentage of refuse burned increased, so did the number of

TABLE 62 ECONOMIC IMPACT OF SCENARIO 5

PARTICULATE CONTROL	KG PER DAY	COST PER KG ($)	COST PER DAY ($)	COST PER YEAR (300 DAYS) ($)
NONE	9.4	0.264	2.48	744
BAG HOUSE	74.8	0.003	0.22	66
WET SCRUBBERS	361.2	0.088	31.79	9,537
ELECTROSTATIC PRECIPITATOR	696.2	0.059	41.08	12,324
HR W/ESP	858.4	0.018	15.45	4,635
TOTAL	2000			27,306

TABLE 63 COMPARISON OF SCENARIOS IN MUNICIPAL SECTOR

SCENARIO	TOTAL NUMBER OF INCINERATORS	PERCENT OF REFUSE BURNED	CARBON FIBER BURNED (KG/DAY)	ANNUAL COST
1. BASELINE CASE	41	4	80	$1,693
2. NEAR FUTURE CASE	51	5	100	$1,828
3. FAR FUTURE CASE	39	8	160	$1,197
4. INTENSIVE ENERGY RECOVERY CASE	487	60	1,200	$ 6,795
5. UPPER BOUND CASE	989	100	2,000	$27,306

incinerators, whereas the annual cost remains quite stable, except in the last case. This is due to the fact that as the amount of refuse burned was increased, the reasonable assumption was made that only the more efficient electrostatic precipitators were installed to process the additional refuse. In the last case, however, all types of precipitators presently in use were increased proportionately. It must be noted that even in this case, the costs are approximately $3000 and thus clearly insignificant. It can thus safely be concluded that the municipal incineration of the carbon fiber in consumer products will not present an economic problem in the post-1990 time period.

DEFINITION OF ALTERNATIVE SCENARIOS FOR INDUSTRIAL WASTE DISPOSAL

Scenario A--Baseline Case

Similar to the municipal sector, a baseline case can be established for the industrial sector by assuming the current industrial procedures for carbon fiber and the present mix of industrial incinerators to exist in 1990.

It is thus assumed (as determined in Section 6) that the aerospace and automobile industries continue to landfill their carbon fiber scrap. Ten percent of the carbon fiber used in automobiles, however, enters the municipal waste stream in the form of after-market specialty items, since 4 percent of municipal waste is incinerated (as mentioned in the previous section); 0.4 percent of carbon fiber used in automobiles is incinerated in municipal incinerators. For purposes of this analysis, it is assumed that these municipal incinerators are not fitted with an active particulate control system. The remaining smaller industrial users do not segregate their waste. Since approximately 4 percent of these industries operate incinerators, the reasonable assumption is made that 4 percent of the carbon fiber waste generated by other industrial uses are incinerated. This leads to a total of 34,545 kg of carbon fiber to be incinerated.

The population of industrial incinerators which was found in Section 7 to process materials containing carbon fiber consists of the following:

- 89% dual chamber
- 6.8% single chamber and conical
- 2.6% fluidized bed
- 1.1% multiple hearth
- 0.5% infrared.

Most of these industrial incinerators were found to have little if any sophisticated pollution control equipment, and the conservative assumption is thus made that these incinerators operate without waste heat recovery or auxiliary afterburners.

For each type of incinerator, the economic cost of carbon fiber is computed as the product of the amount processed by the incinerator type and its impact cost as determined in Section 7. The resulting costs per year are shown in Table 64. The total yearly cost of Scenario A is obtained by summing over all incinerator costs and can be seen in Table 64 to amount to approximately $5,250, a negligible sum.

TABLE 64 ECONOMIC IMPACT OF SCENARIO A

INCINERATOR TYPE	CARBON FIBER INCINERATED (KG/YEAR)	IMPACT COST FUNCTION (COST/KG)	COST PER YEAR ($)
MUNICIPAL	18,181	0.264	4799.78
DUAL CHAMBER (INDUSTRIAL)	14,564	0.0264	384.49
FLUIDIZED BED	425	0.0059	2.51
MULTIPLE HEARTH	180	0.0044	.79
INFRARED	82	0.0022	.18
SINGLE CHAMBER AND CONICAL	1,113	0.0594	66.11
TOTAL	34,545		5253.86

Scenario B--Future Trend Case

As resource recovery and pollution control are emphasized as important parts of national energy and environmental protection policies, the industrial incinerator population is likely to change. In fact no single chamber units are being built now, and most newer units have heat recovery systems as well as afterburners which contain wet scrubbers for particulate control. All the industrial incinerators in the baseline case are therefore assumed to be equipped with heat recovery systems, and the single chamber units to be phased out for a realistic future trend case. This leads to the following industrial incinerator population:

- 95.8% dual chamber
- 2.6% fluidized bed
- 1.1% multiple hearth
- 0.5% infrared.

In this scenario the municipal incinerators are also assumed to be fitted with electrostatic precipitators and heat recovery systems. From Tables 54 and 55 it can be seen that the impact cost functions of all incinerator types with heat recovery systems are significantly lower than before. As shown in Table 65, the total annual cost is then reduced to approximately $470, an even more negligible sum.

TABLE 65 ECONOMIC IMPACT OF SCENARIO B

INCINERATOR TYPE	CARBON FIBER INCINERATED (KG/YEAR)	IMPACT COST FUNCTION (COST/KG)	COST PER YEAR ($)
MUNICIPAL	18,181	0.018	327.30
DUAL CHAMBER (INDUSTRIAL)	15,677	0.0088	137.96
FLUIDIZED BED	425	0.0018	.76
MULTIPLE HEARTH	180	0.0013	.23
INFRARED	82	0.0022	.18
TOTAL	34,545		466.43

Scenario C--Current Upper Bound

In the baseline case the estimates for the incinerator population and associated particulate control systems are representative of the least efficient incinerators currently in industrial use. They are thus conservative estimates, i.e., they lead to higher costs than actually expected. Another conservative assumption in the baseline case is that 10 percent of the carbon fiber in automotive components is to be found in after-market specialty items which eventually enter the municipal waste stream since experts agree that the actual fraction of specialty items is likely to fall well below 10 percent. The assumption that the aerospace industry buries all of its scrap is in accordance with their standard procedures, leaving the disposal of all other (nonaerospace, nonautomotive) industrial waste as the only real uncertainty. For the purpose of creating an upper bound under the current industrial incinerator population, it is thus assumed in this scenario that all of the other industrial waste is incinerated. The resulting costs are shown in Table 66. Although there is an increase of a factor of about 25 over the baseline costs, $131,350 still does not represent a significant annual economic impact to the nation.

Scenario D--Future Upper Bound Case

As in Scenario C, an upper bound is created for the future trend case by assuming again that all of the industrial waste is incinerated. However, in this case, the incinerator population considered is that of Scenario B, i.e., no single chamber units and all other incinerators equipped with heat recovery systems and auxiliary afterburners, as indicated by future trends. The resulting costs are shown in Table 67. The increase in amount of carbon fiber incinerated tends to raise costs while the improved efficiency in incinerator types and particulate control methods tends to decrease costs, and the net result is a minimal economic impact of $11,660.

Scenario E--Worst Possible Case

The worst conceivable case would happen if all of the carbon fiber used in 1990 by the aerospace industry, the automobile industry and all other industrial users were eventually incinerated in the least efficient of all incinerators (municipal with no

TABLE 66 ECONOMIC IMPACT OF SCENARIO C

INCINERATOR TYPE	CARBON FIBER INCINERATED (KG/YEAR)	IMPACT COST FUNCTION (COST/KG)	COST PER YEAR ($)
MUNICIPAL	454,545	0.264	119,999.88
DUAL CHAMBER (INDUSTRIAL	364,090	0.0264	9,611.98
FLUIDIZED BED	10,636	0.0059	62.75
MULTIPLE HEARTH	4,500	0.0044	19.80
INFRARED	2,045	0.0022	4.50
SINGLE CHAMBER AND CONICAL	27,818	0.0594	1,652.39
TOTAL	863,635		131,351.30

TABLE 67 ECONOMIC IMPACT OF SCENARIO D			
INCINERATOR TYPE	CARBON FIBER INCINERATED (KG/YEAR)	IMPACT COST FUNCTION (COST/KG)	COST PER YEAR ($)
MUNICIPAL	454,545	0.018	8181.81
DUAL CHAMBER INDUSTRIAL	391,908	0.0088	3448.79
FLUIDIZED BED	10,636	0.0018	19.14
MULTIPLE HEARTH	4,500	0.0013	5.94
INFRARED	2,045	0.0022	4.50
TOTAL	863,635		11,660.18

particulate control and a yearly impact cost of $0.066 per kg). This is clearly an unrealistic case, but for the purpose of illustration the economic impact of such a scenario is computed as follows:

7,227,272 kg* x $0.264 per kg = $1,907,999

This is clearly a great increase in costs over the past scenarios studies but still does not represent a significant impact on the national level.

NATIONAL ECONOMIC IMPACT OF CARBON FIBER INCINERATION UNDER ALTERNATIVE SCENARIOS FOR INDUSTRIAL WASTE DISPOSAL

Using the same approach as for the municipal sector, five different scenarios of the industrial incineration of carbon fiber were considered and analyzed for their potential national economic impact. The results are summarized in Table 68. Disposal practices were varied separately from the incinerator population and its associated particulate control systems in order to illustrate the sensitivity of results to these esimates. It can be seen that a change in incinerator population to the future trend, i.e., no single chamber units and all other units equipped with heat recovery systems and afterburners, reduced the costs per year in both Scenarios B and D by a factor of about 15 from A and C respectively. On the other hand, varying the current industrial disposal practices to assume that all nonaerospace, nonautomotive industrial scrap is incinerated, increases the annual costs in Scenarios C and D by a factor of about 25 over A and B respectively. In each of the five cases mentioned, however, the annual economic impact for the nation is insignificant, the highest being $37,730 for Scenario C. The insignificance of the economic impact of carbon fiber disposal in the industrial sector is further exemplified by the unrealistic Scenario E in which all industrial waste is incinerated leading to annual costs of $447,000. Even in this extreme case the costs seem insignificant when compared to nonregulated examples such as the cost of corrosion for automobiles which was estimated to amount to $6 million in 1975 [96]. It is true that for a final decision on the significance of a potential half million dollar impact on the national level, the benefit part of a cost/benefit analysis on carbon fiber disposal in the industrial sector remains to be

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*Composite Market Reports, Inc. estimate used.

TABLE 68 COMPARISON OF SCENARIOS IN INDUSTRIAL SECTOR

SCENARIOS*	DISPOSAL PRACTICES	INCINERATOR POPULATION	PARTICULATE CONTROL	COST PER YEAR ($)
A BASELINE CASE	CURRENT INDUSTRY	CURRENT EXISTING	NONE	5,250
B FUTURE TREND CASE	CURRENT INDUSTRY	NO SINGLE CHAMBER	WITH HEAT RECOVERY (+ WET SCRUBBERS)	466
C CURRENT UPPER BOUND	AEROSPACE SCRAP LANDFILLED. 10% AUTOMOBILE +100% ALL OTHER INDUSTRIAL WASTE INCINERATED	CURRENT EXISTING	NONE	131,351
D FUTURE UPPER BOUND	AEROSPACE SCRAP LANDFILLED. 10% AUTOMOBILE +100% ALL OTHER INDUSTRIAL WASTE INCINERATED	NO SINGLE CHAMBER	WITH HEAT RECOVERY (+ WET SCRUBBERS)	11,660
E WORST POSSIBLE CASE	ALL INDUSTRIAL WASTE INCINERATED	LEAST EFFICIENT TYPE (MUNICIPAL)	NONE	1,907,999

*ALL SCENARIOS USE REVISED 1990 ESTIMATE OF CF DEMAND AS BASIS FOR ESTIMATING POST-1990 DISPOSAL LOAD.

studied. This is beyond the scope of this project. However, it must be remembered that the only scenario with any doubt as to economic significance is No. 5, which was considered only as an upper bound and in fact represents an extremely unlikely case. Further study is therefore not recommended.

REFERENCES

1. Carbon Fiber Study, NASA Technical Memorandum 7871B, May 1978.

2. Mahoney, L. R., J. Braslow and J. J. Harwood, "Effect of Changing Automobile Materials on the Junk Car of the Future," SAE Technical Paper Series No. 790299.

3. "40 MPG Average by 1995 Bell Seen Spur to Aluminum Autos," American Metal Market News, March 10, 1980, p. 34.

4. U.S. Department of Transportation, Data and Analysis for 81-84 Passenger Automobile Fuel Economy Standards: Documents 1 to 4, Washington, DC, February 28, 1977.

5. Department of Health, Education and Welfare, "Criteria for a Recommended Standard--Occupational Exposure to Fibrous Glass," NIOSH Publication No. 77-139, Washington, DC, April 1977.

6. Babcock & Wilcox, "DynaTorque^{TM} Graphite Shaft," Advanced Composites Department, Alliance, OH.

7. Kaiser, R., Argos Associates, Inc., Technology Assessment of Advanced Composite Materials, prepared for the National Science Foundation, April 1978, p. 117.

8. Fiott, S., Tennis Equipment, Tennis Research Group, Inc., 1976.

9. Fiott, S., Tennis Equipment, Tennis Research Group, Inc., 1976, p. 48.

10. Irwin Broh & Associates, The Sporting Goods Market in 1979, prepared for the National Sporting Goods Association, Des Plaines, IL, p. 70.

11. "Skateout in Tennis, Equipment Side," New York Times, April 20, 1980.

12. Kaiser, R., Argos Associates, Inc., Technology Assessment of Advanced Composite Materials, Phase I Final Report, prepared for the National Science Foundation, 1978, p. 117.

13. Letter from R. Kaiser, Argos Associates, Inc., to P. Stevenson, ECON, Inc., February 1980.

14. Boehm, H. C., "Influence of Composite Materials on Alpine Ski Design," SAMPE Journal, September/October 1979, p. 14.

15. Boehm, H. C., "Influence of Composite Material on Alpine Ski Design," SAMPE Journal, September/October 1979, p. 17.

16. Irwin Broh & Associates, The Sporting Goods Market in 1979, prepared for the National Sporting Goods Association, Des Plaines, IL, 1979, p. 60.

17. Devault, J. B., "Overview of Commercial Applications for Graphite Composites," Hercules, Inc., National SAMPE Symposium, 1975.

18. Irwin Broh & Associates, The Sporting Goods Market in 1979, prepared for the National Sporting Goods Association, Des Plaines, IL, 1979, pp. 38-39.

19. Kaiser, R., Argos Associates, Inc., Technology Assessment of Advanced Composite Materials, Phase I Final Report, prepared for the National Science Foundation, 1978, p. 118.

20. Graftek/Exxon Enterprises, "High Performance Sports Equipment," Fishing Division, Cocoa, FL, 1979.

21. Kaiser, R., Argos Associates, Inc., Technology Assessment of Advanced Composite Materials, Phase I Final Report, prepared for the National Science Foundation, 1978, p. 117.

22. Hamilton, R. S., The Carborundum Co., Niagara Falls, NY, personal communication with R. Kaiser, March 6, 1978.

23. Dowell, M. B., "Using Carbon Fibers to Reinforce Plastics," Plastics Engineering, April 1977, p. 31.

24. Molyneux, M. and B. R. Lyons, "Carbon Fiber Reinforced Plastics Part in Radiological Equipment," 33rd Annual Technical Conference, Reinforced Plastics/Composites Institute, The Society of Plastics Industry, Inc., Paper 12-E, Washington, DC, 1978.

25. Bokros, J. C. et al., "Prostheses Made of Carbon," Chemtech, January 1977, pp. 40-49.

26. Jenkins, G. M. and F. X. DeCarvalho, "Biomedical Applications of Carbon Fiber Reinforced Carbon in Implanted Prostheses," Carbon, Vol. 15, 1977., pp. 33-77.

27. Harvey, H. R. and D. J. Chopinsky, "Development of a Motor Vehicle Materials Historical, High Volume Industrial Processing Rates Cost Data Bank (Intermediate Type Car)," Pioneer, Inc., Report to U.S. Department of Transportation, Contract No. DOT-HS-5-01081, December 1976.

28. Chang, D. C. and J. W. Justusson, "Structural Requirements in Materials Substitution for Car-Weight Reduction," presented at SAE Automobile Engineering Congress, Detroit, MI, Paper No. 760023, February 1976.

29. Kliger, H. S., "Development and Experimental Verification of Design Values for Carbon-Glass Hybrid Sandwich Composites," Composite Materials in The Automobile Industry, ASME Monograph H00115, 1978.

30. Kaiser, R., Argos Associates, Inc., "Automotive Uses of Advanced Composite Materials," Report to U.S. Department of Transportation, Contract No. DOT-HS-7-01739, December 1978.

31. Society of the Plastics Industry, Inc., Facts and Figures of the Plastics Industry, 1976 Edition, New York, NY.

32. U.S. Department of Labor, Wholesale Prices and Price Indexes--Data for July 1977, Bureau of Labor Statistics, Washington, DC.

33. Williams, G. L., "A New Approach to Sheet Molding Compound (SMC) Molding," Proceedings of the 31st Annual Technical Conference, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., Section 2-D, Washington, DC, 1976.

34. Simko, T. D., "Automotive and Commercial High Strength Molding Compounds," Proceedings of the 33rd Annual Technical Conference, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., Section 18-G, Washington, DC, 1978.

35. Ackley, R. H., "XMC^{TM} Structural GFRP for Matched Metal Die Molding," Proceedings of the 31st Annual Technical Conference, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., Section 16-C, Washington, DC, 1976.

36. PPG Industries, Inc., Phase II--Fast Cure Automotive SMC, Technical Information Bulletin, PT, Pittsburgh, PA, May 31, 1978.

37. Fesko, D. G., P. K. Mallick and S. Newman, "Automotive Composites--Manufacturing and Materials Interactions," Composite Materials in the Automobile Industry, American Society of Mechanical Engineers, New York, NY, 1978.

38. Martin, J., "Pultrusion--An Overvew of Applications and Opportunities," Proceedings of the 33rd Annual Technical Conference, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., Section 8-H, Washington, DC, 1978.

39. Tickle, J. D., "Pultrusion--Step Up the Challenge to Structural Steels," Machine Design, October 2, 1977, pp. 163-167.

40. Wood, A. S., "Pultrusion Is Poised for New Growth," Modern Plastics, June 1976.

41. Rolston, J. A., "Process and Economic Factors for Pultrusion," Proceedings of the 33rd Annual Technical Conference, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., Washington, DC, 1978.

42. Sanada, M., "Economics of Plastic Molding Processes," Proceedings, SPI 31st Annual Technical Conference, Montreal, Canada, May 7-10, 1973, p. 237.

43. Haddad, G. N., "Recent Innovations in PVC-FRP Composite Pipe," Proceedings of the 33rd Annual Technical Conference, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., Section 5-F, Washington, DC, February 1977.

44. Lionetta, W. G., Jr., "Sources of Innovation Within the Pultrusion Industry," S.M. Thesis, Alfred P. Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA, June 1977.

45. Adams, D. G., J. A. DiCello, C. Hoppe, A. S. Kaiser, A. N. Kersoglanand and W. W. McVinnie, "High Strength Materials and Vehicle Weight Reduction Analysis," SAE Paper 750221, 1975.

46. Motor Vehicle Manufacturers Association of the United States, Inc., MVMA Motor Vehicle Facts and Figures 1979, Detroit, MI, 1979.

47. American Trucking Associations, Inc., American Trucking Trends 1977-1978, Department of Research and Statistical Services, Washington, DC, 1978, p. 30.

48. American Trucking Associations, Inc., American Trucking Trends 1977-1978, Department of Research and Statistical Services, Washington, DC, 1978, p. 29.

49. Laird Durham Co., Trucking in 1995, prepared for the Motor Vehicle Manufacturers Association, San Francisco, CA, 1975, p. 9.

50. Motor Vehicle Manufacturers Association of the United States, Inc., MVMA Motor Vehicle Facts and Figures 1979, Detroit, MI, 1979, p. 11.

51. Bauer, J. L., A Review of Composite Material Applications in the Automotive Industry for the Electric and Hybrid Vehicle, prepared for the U.S. Department of Energy, Office of Transporation Programs by the Jet Propulsion Laboratory, Pasadena, CA, 1978, pp. 5-7.

52. Motor Vehicle Manufacturers Associations of the United States, Inc., MVMA Motor Vehicle Facts and Figures 1979, Detroit, MI, 1979, p. 57.

53. American Trucking Associations, Inc., American Trucking Trends 1977-1978, Department of Research and Statistical Services, Washington, DC, 1979, p. 21.

54. Murphy, R. W., "Improvements in Fuel Economy and Productivity Through Use of Lightweight Components in Heavy Duty Highway Trucks," Freightliner Corporation, November 1, 1979.

55. Aluminum Company of America, "Economics of Weight Saving in Motor Carrier Operations," 1970.

56. Rockwell International, "Advanced Composites in Automotive Components," SP-7926, 1979.

57. Tickle, J. D., "Pultrusion--Step Up the Challenger to Structural Steels," Machine Design, October 2, 1977, pp. 163-167.

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58. Wood, A. S., "Pultrusion Is Poised for New Growth," Modern Plastics, June 1976.

59. Rolston, J. A., "Process and Economic Factors for Pultrusion," Proceedings of the 33rd Annual Technical Conference, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., Washington, DC, 1978.

60. Fresko, D. G., P. K. Mallick and S. Newman, "Automotive Composites--Manufacturing and Materials Interactions," Composite Materials in the Automobile Industry, American Society of Mechanical Engineers, New York, NY, 1978.

61. ECON, Inc., "The Demand for Advanced Composite Materials in the Automotive Industry, Projections for the Eighties," February 12, 1979, p. 127.

62. Goldsworthy, W. B., Goldsworthy Engineering Company, Torrance, CA, personal communication with R. Kaiser, May 12, 1978.

63. Tessier, N., U.S. Army, AMMRC, Watertown, MA, personal communication with R. Kaiser, June 9, 1978.

64. Dharan, C. K., Ford Aerospace and Communications Corporation, Palo Alto, CA, personal communication with R. Kaiser, May 15, 1978.

65. Sanada, M., "Economics of Plastic Molding Processes," Proceedings SPI 31st Annual Technical Conference, Montreal, Canada, May 7-10, 1973, p. 237.

66. ECON, Inc., "The Demand for Advanced Composite Materials in the Automotive Industry, Projections for the Eighties," February 12, 1979, p. 143.

67. Harvey, M. R. and D. J. Chupinsky, "Development of a Motor Vehicle Materials Historical High-Volume Industrial Processing Rates Cost Data Bank (Compact Type Car)," Report, DOT-HS-802066, NTIS Report PB-262-118, October 1976.

68. Devault, J. B., "Overview of Commercial Applications for Graphite Composites," 20th National SAMPE Symposium and Exposition, San Diego, CA, May 1, 1975.

69. The Society of the Plastics Industry, Inc., "Facts and Figures of the Plastics Industry," New York, NY, 1977.

70. Molyneux M. and B. R. Lyons, "Carbon Fiber Reinforced Plastics Part in Radiological Equipment," Proceedings of the 33rd Annual Technical Conference, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., Paper 12-E, Washington, DC, 1978.

71. Office of Science and Technology, "Carbon/Graphite Composite Material Study," Second Annual Report, 1979.

72. Composite Market Reports, Inc., "Annual Market Estimate of Graphite, Prepreg and Fiber, 1979 Through 1985," July 1980.

73. Burg, M., "DOC Carbon Fiber Production and Demand Estimates," Memo to ECON, Inc., February 2, 1980.

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74. Burg, M., Composite Market Report, Inc., private communication, April 25, 1980.

75. Thompson J., U.S. Environmental Protection Agency, Office of Solid Waste Management, Washington, DC, personal communication with C. Prevost, ECON, Inc., Princeton, NJ, May 1980.

76. Niessen, W. R. and A. F. Sarofim, "Incinerator Air Pollution: Facts and Speculation," Proceedings of the 1972 National Waste Processing Conference, ASME, New York, NY, 1972, p. 167.

77. Sarofim, A. F., Massachusetts Institute of Technology, Department of Chemical Engineering, Cambridge, MA, personal communication with R. Kaiser, Argos Associates, Winchester, MA, April 26, 1980.

78. Walker, A. B. and F. W. Schmitz, "Characteristics of Furnace Emissions from Large Mechanically-Stoked Municipal Incinerators," Proceedings of the 1966 National Incinerator Conference, ASME, New York, NY, 1966, p. 64.

79. Municipal Incinerator Enforcement Manual, EPA-340/1-76-013, January 1977, p. 39.

80. The Accurex Corporation, "Source Category Survey, Industrial Incinerators--Section 4: Population Growth Trends," EPA-450/3-80-13, May 1980.

81. Risk to the Public from Carbon Fibers Released in Civil Aircraft Accidents, National Aeronautics and Space Administration, NASA SP-448, 1980.

82. The Bionetics Corporation, "Final Report for Data Base Review and Assessment of Carbon Fiber Release Into the Environment, Section 2: Literature Search, Section 6: Disposal Techniques," September 12, 1980.

83. "Standard Industrial Classification Manual 1972," U.S. Government Printing Office, Stock No. 041-001-00066-6.

84. U.S. Bureau of the Census, "Census of Manufacturers," Volume 1, Summary, 1972.

85. National Center for Resource Recovery, Inc., "Resource Recovery Activities," Washington, DC, September 1979.

86. Pyle, F. B., "The Taming and Housebreaking of Refuse Shredders," Proceedings of the 1978 National Waste Processing Conference, ASME, New York, NY, 1978, p. 215.

87. Robinson, W. D., "Shredding Systems for Mixed Municipal and Industrial Solid Wastes," Proceedings of the 1976 National Waste Processing Conference, ASME, New York, NY, 1976, p. 249.

88. Thompson, J., U.S. Environmental Protection Agency, Office of Solid Waste Management, Washington, DC, personal communication with C. Prevost, ECON, Inc., Princeton, NJ, June 1980.

89. Hall, J., U.S. Department of Commerce, U.S. Fire Data Center, Washington, DC, personal communication with C. Prevost, ECON, Inc., Princeton, NJ, June 1980.

90. Wilson, D. G., Editor, The Treatment and Management of Urban Solid Waste, Chapter 6, "Landfill," Westport, CN: Technomic Publishing Co., 1972.

91. Supplement No. 8 for Compilation of Air Pollutant Emission Factors, 3rd Edition, AP-42, Supplement 8, Section 2.4, "Open Burning," U.S. Environmental Protection Agency, Office of Air and Waste Management, Office of Air Quality Planning and Standards, Research Triangle Park, NC, May 1978.

92. Alvarez, R. J., Solid Waste Management, updated by Accurex, Internal Memorandum, March 18, 1980, follow-up telephone calls by R. Bruce, NASA consultant to Bionetics, November 1978, p. 104.

93. National Center for Resource Recovery, Inc., "Resource Recovery Activities," Washington, DC, March 1979.

94. National Center for Resource Recovery, Inc., "Resource Recovery Activities," Washington, DC, September 1979.

95. U.S. Environmental Protection Agency, Office of Water and Waste Management, "Solid Waste Facts," Washington, DC, October 1979, p. 14.

96. Payer, J. H., D. G. Dippold, W. K. Boyd, W. E. Berry, E. W. Brooman, A. R. Buhr and W. H. Fisher, Economic Effects of Metallic Corrosion in the United States, Appendix B, Part 2, prepared for The Department of Commerce, National Bureau of Standards by Battelle Columbus Laboratories, NBS Special Publication 511-2, May 1978.